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Condensation and Evaporation Characteristics of Flows Inside Vipertex 1EHT and 4EHT Small Diameter Enhanced Heat Transfer Tubes

David J. Kukulka[a,*], Rick Smith[b], Wei Li[c], Aifeng Zhang[d], He Yan[d]

[a]State University of New York College at Buffalo, 1300 Elmwood Avenue, Buffalo, New York, USA
[b]Vipertex, 658 Ohio Street, Buffalo New York, USA
[c]Zhejiang University, 866 Yuhangtang Road, Hangzhou 310027, China
[d]Qingdao University of Science and Technology, 99, Songling Road, Qingdao City, China
kukulkdj@buffalostate.edu

Results are presented here from an experimental investigation on tubeside condensation and evaporation heat transfer that took place in three Vipertex stainless steel enhanced heat transfer tubes (1EHT-2, 2EHT-2 and 4EHT). Equivalent outer diameter of the tube was 9.52 mm (0.375 in) and the inner diameter was 8.32 mm (0.3276 in). The test apparatus included a horizontal, straight test section with an active length heated by water circulated in a surrounding annulus. Constant heat flux was maintained and refrigerant quality varied.
Condensation experimental runs were performed using R410A as the working fluid; over the inlet quality range of 0.2– 0.8; for mass flux values that ranged from 150 to 460 kg/(m^2 s). In a comparison of condensation heat transfer performance, the enhanced 1EHT-1 tube has best heat performance followed by the enhanced 4EHT tube and finally the 1EHT-2 tube. The highest pressure drop increase was seen in the 1EHT-1 tube followed by the 4EHT tube and the 1EHT-2 tube. The evaporation experiments were performed using R410A at a constant saturation temperature of 279 K; for a mass flux that ranged from 160 to 390 kg/(m^2 s). Inlet and outlet vapor qualities were fixed at 0.2 and 0.8, respectively. As the mass velocity increased, the heat transfer coefficient and pressure drop penalty increase accordingly. Experimental results show a slightly larger pressure drop in the 1EHT-1 tube. The pressure drop in the three EHT tubes could be attributed to the dimples and protrusions in the surface structure, which produce an increased density of nucleation sites. In addition, it was found that the evaporation pressure drop increases with the increasing depth of the dimples. Condensation and evaporation performance is mainly due to the increase in the heat transfer surface area and the increase of interfacial turbulence; this produces flow separation, secondary flows and a higher heat flux from the wall to the working fluid.
Enhanced heat transfer tubes are important options to be considered in the design of high efficiency systems. A wide variety of industrial processes involve the transfer of heat energy during phase change and many of those processes employ old technology. These processes are ideal candidates for a redesign that could achieve improved process performance. Vipertex enhanced tubes recover more energy and provide an opportunity to advance the design of many heat transfer products.

1. Introduction

Enhancement of the heat transfer coefficient in a two-phase heat exchanger is a very important consideration for various air conditioning, power and multiphase flow heat exchanger applications. Several previous studies have been performed that have evaluated some aspects of enhanced heat transfer tubes. Christians et al. (2010) studied film condensation of refrigerants on enhanced tubes. Kekilkcioglu et al. (2016) studied the thermo-hydraulic performance of coiled-wire inserts in a circular tube. Cavallini et al. (2003) presented a detailed review of condensation heat transfer in smooth and enhanced tubes. The enhanced tubes geometries in the present study [as illustrated by Webb and Kim (2004)] is neither a classic integral roughness (little surface area increase) tube, nor a finned tube (surface area increase with no flow separation). It can be considered to be

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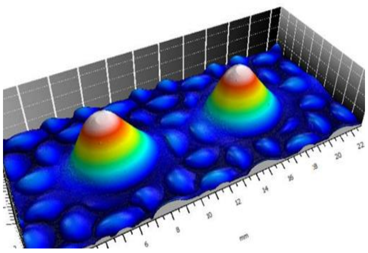
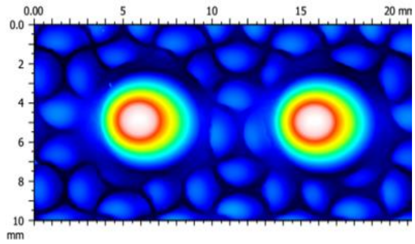
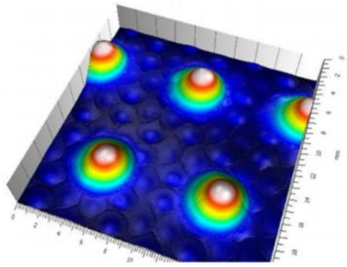
more of a hybrid surface that increases surface area and produces flow separation as a result of the various surface patterns. Those inner and outer surface enhancements create increased heat transfer through a combination of: surface area increase, increased turbulence, boundary layer disruption and secondary flow generation, as pointed by Kukulka et al. (2014) where heat transfer performance of three dimensional enhanced surfaces were studied. Thermal-hydraulic performance of an enhanced dimple tube was evaluated by Li et al. (2016) using experimental and numerical simulation techniques in a pipe-in-pipe heat exchanger. Guo et al. (2015) evaluated convective condensation and evaporation of R22, R32 and R410A inside enhanced tubes at low mass fluxes. Thome (2004) reported tube side evaporation and condensation for various micro-fin tubes for a variety of fluids. Li et al. (2017) found that many rib geometries may play a significant role on enhancing mixed convection. Kukulka et al. (2017) evaluated the inside condensation and evaporation heat transfer of R410A, R22 and R32 that took place here in several 12.7 mm EHT horizontal cooper tubes with low mass fluxes.
The three types of tubes investigated in the present study include three-dimensional tubes that have been produced using multiple enhancement characters; 1EHT tubes (1EHT-1 and 1EHT-2) are made of dimple arrays and longitudinal grooves, with the depth of dimples varying and the details are shown in Figure 1 (a - f). These enhanced surfaces are an enhanced hybrid surface that achieves its enhancement by using various dimples with different heights. There are no correlations that accurately predicts the performance of three-dimensional enhanced heat transfer tubes; therefore, experimental research is a more accurate representation of heat transfer performance.



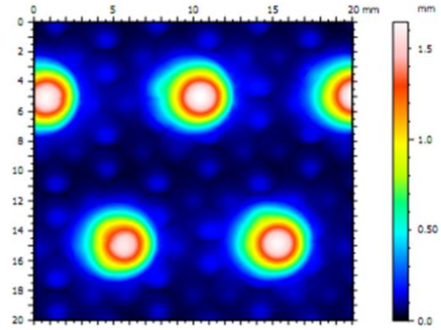
(a) 1EHT-1 three-dimensional view



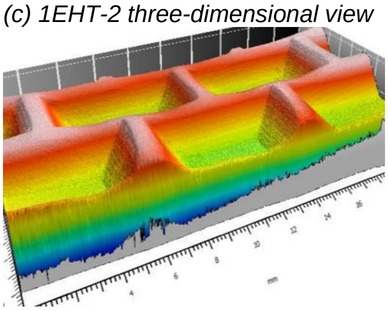
(b) 1EHT-1 false color view



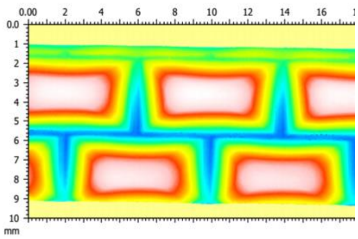
(c) 1EHT-2 three-dimensional view



(d) 1EHT-2 false color view



(e) 4EHT three-dimensional view



(f) 4EHT false color view

*Figure 1**:** Non-Contact Profilometer representation of the surface enhancement structures*

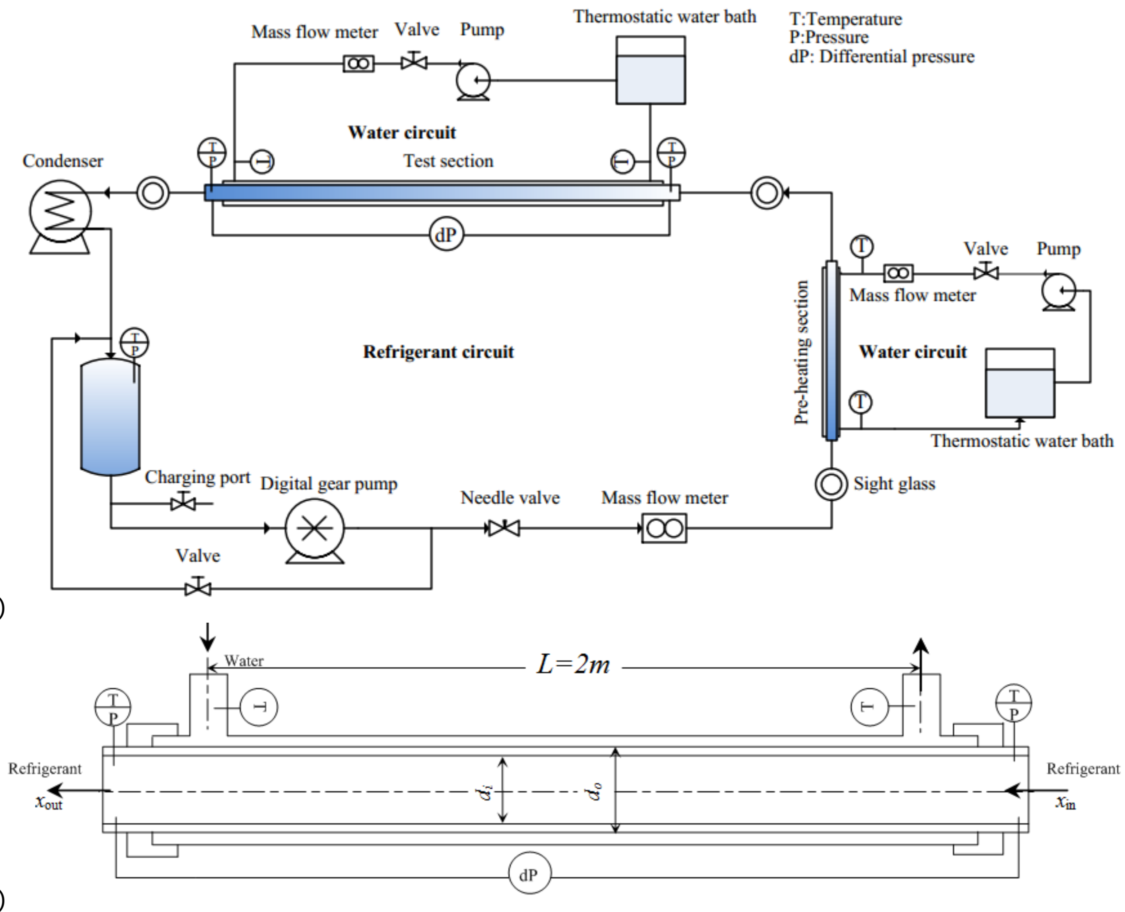
2. Experimental details

2.1 Experimental apparatus

An overall schematic of the experimental test apparatus that is used to evaluate the outside tube condensation is showed in Figure 2 a. It consists of two closed loops: (i) a refrigerant flow circuit which contains the test section, and (ii) a water circuit which can cool or heat the test section. Figure 2 b shows the straight, 2 m long horizontal test section that is part of the counter-flow, double-tube heat exchanger. The refrigerant flows in the tube and cold water flows outside the tube. In order to minimize heat losses, the entire test facility is well insulated. Additional experimental detail is given in Kukulka et al. (2017).

2.2 Experimental test conditions

Condensation heat transfer evaluations were performed using refrigerant R410A at a saturation temperature of 318 K; for a mass flux range of 150 - 460 kg/(m^2 s); 0.8 inlet quality and 0.2 outlet quality; with an average quality of 0.5 being applied for the process. Experimental heat transfer results are limited to average values since the measurement positions are only at the inlet and the outlet of the test section.
The evaporation experiments were performed using R410A as the working fluid for a constant saturation temperature of 279 K; the mass flow rate values varied from 160 kg/(m^2 s) to 390 kg/(m^2 s). Inlet and outlet vapor qualities are 0.2 and 0.8. An average vapor quality of approximately 0.5 was used for all evaporation tests. The mass flow rate was calculated using the internal cross-sectional flow area and the heat exchange amount was determined using the total inner surface heat-transfer area.



(a)

(b)

Figure 2: Schematic of (a) the experimental apparatus; (b) test section

3. Results

3.1 Condensation single-phase heat transfer

In order to confirm the experimental heat loss for the test section, water and refrigerant measurements were made for various heat exchange conditions. Figure 3a shows the single-phase heat transfer for R410A inside the three enhanced tubes. As the mass flux rate increases, the tubes demonstrate similar heat transfer characteristics; 1EHT-1 tube has the highest heat transfer coefficient, h, and is approximately 1.4 - 1.8 times of the h of the smooth tube; while the 1EHT-2 and 4EHT tubes have similar values of h over the same mass flux range. For all the conditions the enhanced tubes show better heat transfer performance than a smooth tube. Fig. 3 b shows an increase in pressure drop for increasing mass flux values; and values for all four tubes show minor differences; In general it appears that higher heat transfer performance leads to a slightly higher frictional pressure drop; this is demonstrated in the 1EHT-1 tube which has the highest h and the highest pressure drop. Pressure drop values for the 4EHT and 1EHT-2 tubes are very similar to a smooth tube. The structure of the 1EHT-1 tube is more enhanced and is the reason for the enhanced performance and larger pressure drop.

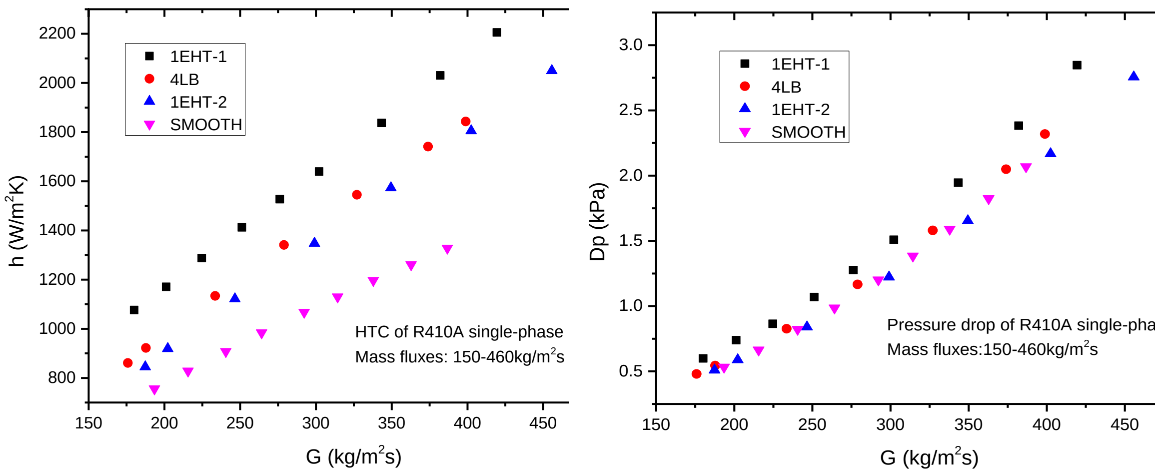


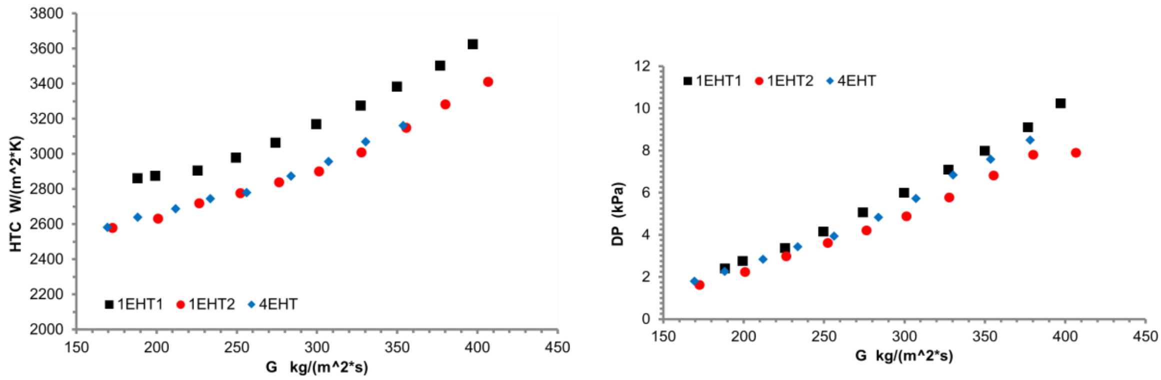
Figure 3: (a) Single-phase heat transfer coefficient versus mass flux for 1EHT-1, 1EHT-2, 4EHT and smooth tubes; (b) Single-phase pressure drop versus mass flux for 1EHT-1, 1EHT-2, 4EHT and smooth tubes

3.2 Two phase heat transfer

Fig.4a shows the condensation heat transfer coefficient trend of the 1EHT-1, 1EHT-2, and 4EHT tubes. The relationship between the heat transfer coefficient and mass flux is obtained by changing the flow rate of refrigerant R410A. Condensation heat transfer coefficient increases proportionally with increasing mass flow rate; with the 1EHT-1 tube showing a condensation heat transfer coefficient that is in the range of 2,800 – 3,600 W/(m^2 K). The 1EHT-2 and 4EHT tubes have slightly lower heat transfer performance. This is a function of the enhancement structure utilized causing the upper concave region to retain liquid refrigerant. In addition to an increase in surface area, the main reasons for the condensation enhancement of the enhanced tubes is increased turbulence and increase fluid separation; the fine background pattern produces a fracture of the boundary layer causing additional fluid mixing that also enhances heat transfer. Finally, under the action of the gas shear force, the liquid in the sunken surface structure migrates again and also increases the effect of heat exchange.

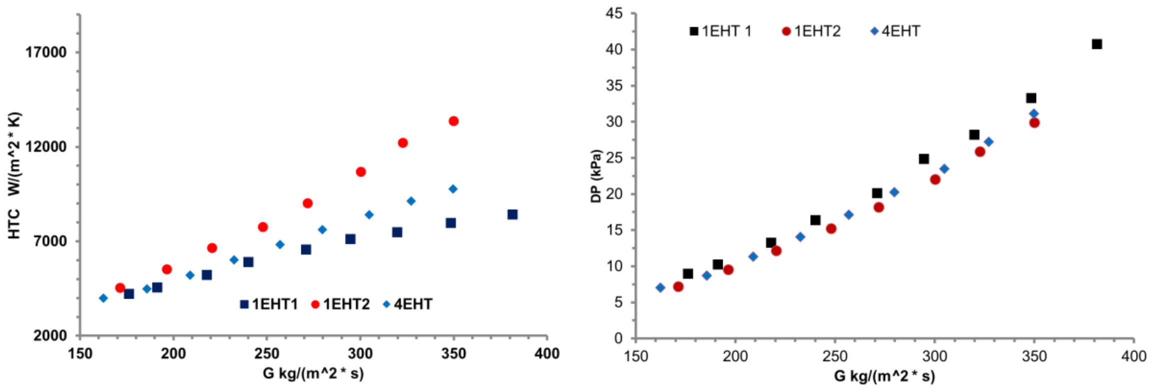
Figure 4b presents the relationship between mass flux and the pressure drop for R410A inside the three enhanced tubes. As can be seen the three tubes exhibit similar pressure drop characteristics; with 1EHT-1 exhibiting the largest pressure drop, followed by the 4EHT tube and finally the lowest pressure drop being the 1EHT-2 tube. Additional surface area produces more turbulence in the liquid film; and the 1EHT-2 tube has an enhanced surface area with little/no fluid separation; exhibiting the lowest pressure drop. Some comparisons can be made to Kukulka et al. (2017), in that study the same fluid was used, with a lower range of mass flow rates; however larger copper tubes were used instead of 9.52 mm OD stainless steel tubes. Lower rates of heat transfer are seen in the present study for similar flow rates. An experimental study was conducted by Ayub et al. (2017) on an enhanced dimpled tube in order to evaluate the in-tube two phase heat transfer and pressure drop performance in an annular section created between the enhanced tube and a solid round rod. They found a three times enhancement in the dimpled tube.

Evaporation results for R410A in the enhanced tubes (1EHT-1, 1EHT-2,4EHT) is presented in Figure 5. Conditions were controlled at a saturation temperature 6 °C (279.15 K); with a mass flow rate that was in the range from 160 to 390 kg/(m^2 s); with the inlet and outlet vapor quality of 0.2 - 0.9. Figure 5a shows the heat transfer coefficient as a function of mass flux for the various enhanced EHT tubes. For all the tubes, the evaporation heat transfer coefficient increases with an increasing mass flow rate; with the 1EHT-2 tube providing the largest heat transfer. The variation of the evaporation heat transfer coefficient for the 1EHT-1 tube and the 4EHT tube is similar when the mass flow rate is < 250 kg / m^2 s. As the mass flow rate increases, the evaporation heat transfer coefficient of the 1EHT-1 tube increases slightly when compared to the 4EHT tube. Comparing the 1EHT-2 tube (shallow dimples) to the three-dimensional structure (deep dimples) on the surface of the 1EHT-1 tube or the surface structure found in the 4EHT tubes; the 1EHT-1 and 4EHT enhancement is deeper; resulting in a more intense turbulent mixing zone. Under the condition of a high flow rate, the turbulence intensity increases due to the influence of the enhancement factors. Additionally, when considering the 1EHT-1 and 4EHT tubes the liquid film may burn dry, with bubbles present in the annular flow, and increased bubble area coverage on the pipe wall, forming a vapor film that impedes the heat transfer. Some comparisons can be made to Kukulka et al. (2017), here the same fluid was used, with a lower range of mass flow rates; however larger copper tubes were used instead of 9.52 mm OD stainless steel tubes. Lower rates of heat transfer are seen in the present study for similar flow rates.



(a) (b)

Figure 4: (a) Condensation heat transfer coefficient as a function of mass flux for 1EHT-1, 1EHT-2, and 4EHT tubes; (b) Condensation pressure drop as a function of mass flux for 1EHT-1, 1EHT-2, and 4EHT tubes



(a) (b)

Figure 5: (a) Evaporation heat transfer coefficient as a function of mass flux for 1EHT-1, 1EHT-2, and 4EHT tubes; (b) Evaporation pressure drop as a function of mass flux for 1EHT-1, 1EHT-2, and 4EHT tubes

4. Conclusions

An experimental study was performed to study the evaporation / condensation heat transfer characteristics and pressure drop of several kinds of three-dimensional heat transfer tubes. In general, heat transfer enhancement performance of these tubes can be summarized as follows:

1 The 1EHT-1 has the best heat transfer performance in the R410A single-phase experiment, about 1.4-1.8 times of smooth tube at mass flux considered in this study. The heat transfer of the 1EHT-2 and 4EHT tubes are similar to each other, but larger than the smooth tube. Pressure drop increases with increasing mass flux rates; the 1EHT-1 tube produces slightly larger pressure drop values followed by the 1EHT-2 and 4EHT tubes.
2 In R410A condensation, the 1EHT-1 tube has the best heat transfer performance, followed by the 4EHT tube and finally the 1EHT-2 tube.
3 Condensation pressure drop values for the 1EHT-1 tube is the highest, followed by the 4EHT tube and finally the 1EHT-2 tube.

An experimental study of the evaporation performance in three enhanced surface heat transfer tubes and was carried out at the saturation temperatures of 6 ℃. Friction pressure drop and mean heat transfer coefficients were presented, with the following conclusions being made:

1 Evaporation heat transfer performance of the three enhanced tubes were presented. The 1EHT-2 tube has the highest heat transfer coefficient.
2 Evaporation pressure drop performance for the three EHT tubes were experimentally determined. Pressure drop in all three EHT tubes are approximately the same; although the 1EHT-1 pressure drop is slightly higher than the others.

The most noteworthy result is that the 1EHT-2 tube performs the best under evaporation conditions; initially it was expected that the 1EHT-1 would perform the best, however this was no found not to be the case. This trend demonstrates an unusual trend in three dimensional tubes and it deserves additional work.

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