A Review of the Influence of Microfin Enhancements on the Condensation Heat Transfer Coefficient for Small Diameter Tubes

ABSTRACT

This white paper reviews the relationship between condenser coil tube diameter, internal tube enhancements, and the resultant influence on heat transfer coefficient (HTC). Helical microfins are the primary enhancement of interest, specifically for condenser applications for tube diameters ranging from 9.5 mm to 3 mm outer diameter (OD). Several other tube enhancements, such as herringbone fins and surface microstructures, are also considered. The main findings can be summarized as follows:

1. *Reducing the tube diameter of a smooth tube increases its HTC.*
2. *The flow pattern of vapor refrigerant through a condenser tube changes as the refrigerant condenses. An annular flow pattern exhibits the highest HTC.*
3. *Helical fins delay the transition from an annular flow pattern to stratified or wavy flow, thereby enhancing the HTC of the tube (9.52 mm OD) by as much as 300%.*
4. *The effectiveness of helical microfins diminishes as the tube diameter decreases. For example, for 9.52 mm tubes, microfins increase the HTC of a smooth tube by as much as 300%, whereas the increase for 3 mm tube is approximately 150%.*
5. *While the enhancement factor for helical microfins reduces with decreasing tube diameter, the absolute HTC for enhanced tubes is generally higher than that of smooth tubes. That difference is not as significant for 3 mm tubes, however.*
6. *At high refrigerant mass flux flows, herringbone microfins substantially outperform helical microfins.*
7. *Surface microstructures (surface roughness, nanotube bundles) have shown to increase the HTC for submillimeter size tubes, especially for evaporation applications in the electronics industry.*
8. *For heat exchangers with 5mm tubes, the use of microfins can increase heat capacity up to 21% or reduce pressure drop up to 11%, fin material mass up to 10%, and tube material mass up to 17% over similar heat exchangers with regular smooth tubes.*
9. *The geometry and structure for tube enhancements has been limited by manufacturing processes. A non-mechanical expansion process may provide a method to develop more intricate and effective internal tube enhancements.*

Additional work is warranted to understand how microfins influence the performance of tubes during evaporation. Past research on microstructures has mainly focused on electronics cooling applications, however, due to their effectiveness at very small tube sizes, additional research should be conducted for larger-scale HVAC and refrigeration applications.

INTRODUCTION

In order to reduce the energy consumption, manufacturing cost and material weight of a heat exchanger, the HVAC&R industry has recently considered both reducing the tube diameter and employing internal tube enhancements to augment the heat transfer on the refrigerant side. Corrugated tubes (Barba et al., 2002), helical wire inserts (Setumadhavan and Rao, 1983), herringbone fins (Miyara et al., 2000), and helical microfins (Cavallini at al., 2003) are some examples of the internal enhancements that have been developed and researched. Out of these enhancements, corrugated tubes and helical wire inserts are primarily used for single phase liquid flows, whereas herringbone (Figure 1a) and helical microfins (Figure 1b) are used for two-phase flows. For very small diameter tubes, where the outer diameter (OD) is less than 1mm, surface roughness (Figure 1c) and microstructures have also shown to improve performance, especially during evaporation. The significance of these enhancements, particularly over smooth tubes at smaller diameters, is largely unknown and serves as the topic of this white paper.

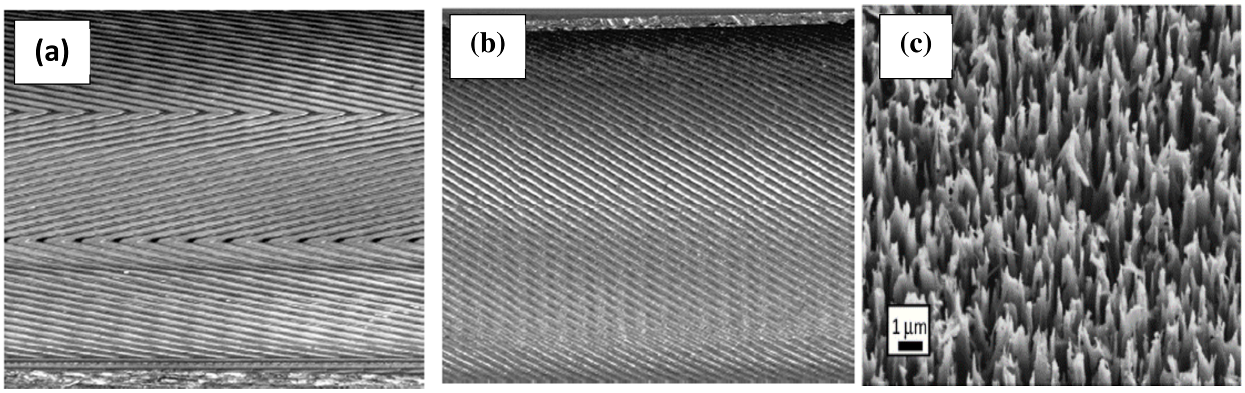

Figure 1. Internal enhancements to augment the heat transfer on refrigerant side. (a) Herringbone fins; (b) helical microfins; (c) microstructures.

The present document will outline:

- Benefit of small diameter tubes (3 – 5 mm OD) over conventional tube sizes (7 – 9 mm OD);
- Impact of internal tube enhancements on smaller (3 – 5 mm OD) diameter tubes;
- Impact of internal tube enhancements in the form of surface microstructures; and,
- Benefits of various manufacturing approaches for developing internal tube enhancements.

In the first section, the basics of two-phase condensation flow patterns are reviewed, including a discussion of the influence of microfins. The second section outlines identified trends for the enhancement of the heat transfer coefficient (HTC) for enhanced tubes with respect to parameters such as tube diameter and mass flux for helical microfins and microstructures. Conclusions are summarized in the final section.

TWO-PHASE FLOW PATTERN FOR CONDENSATION

For two-phase flows, the distribution of liquid and vapor phases in the flow channel is an important aspect of their description. Their respective distributions take on some commonly observed flow structures, with particular identifying characteristics, often including HTC and pressure drop behavior. For instances with a low mass flux (below 300 kg/m^2/s), as shown in Figure 2a, as the refrigerant vapor enters the tube from the left, it condenses along the tube perimeter and forms an *annular* film. As the refrigerant continues down the length of the tube, the amount of condensate increases, especially at the bottom of the tube, creating *stratified* flow. Further downstream, shearing action generates waves on the condensate accumulated at the bottom of the tube and the flow is considered to be *wavy*. If the mass flux is high (above 300 kg/m^2/s), as shown in Figure 2b, the condensate partially or completely fills up the tube cross section. This gives rise to a *slug* or *elongated bubble* flow regime. Of the flow patterns that develop, an annular flow pattern produces the highest HTC. Typically in any condenser tube, 50 to 70% of the tube volume is occupied by annular flow. The goal of any internal enhancement is to delay the development of stratified or wavy flow patterns, effectively increasing the length of the annular flow regime.

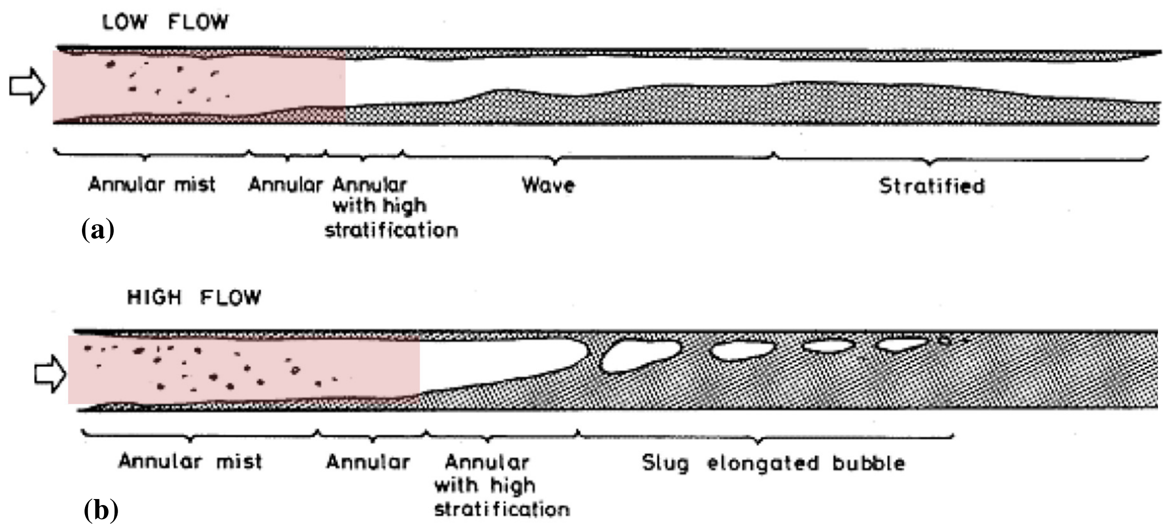

Figure 2. Condensation flow pattern for (a) Low mass flux (Thome (2003)); and (b) High mass flux (Collier and Thome (1998))

Figure 3 shows this effect on a flow pattern map for enhancements in an approximately 9.5 mm outer diameter tube for multiple refrigerants. The vertical lines indicate the vapor quality (x) at which the flow pattern transitions from annular to intermittent (stratified, wavy, slug, etc.). For smooth tubes, this transition occurs at x =0.45 (for R22), whereas for helical fins, this transition takes place at about x=0.25. The curved horizontal line shows the transition with respect to the mass flux. One can see that microfins lower the mass flux at which the annular flow pattern transitions to other regimes. Thus, internal enhancements delay the transition, enabling increased heat transfer performance.

Figure 4 illustrates this delay in transition for R134a refrigerant for a tube with an outer diameter of 8 mm. Under the same conditions, the flow inside the microfin tube is annular whereas the flow inside the smooth tube is stratified. The exact reason behind this delay in transition is still unknown. However, it is widely believed that centrifugal action induced by swirling from the microfins plays an important role in this behavior. Many researchers also believe that the increased surface area and increased level of turbulence caused by the microfins help to enhance the HTC.

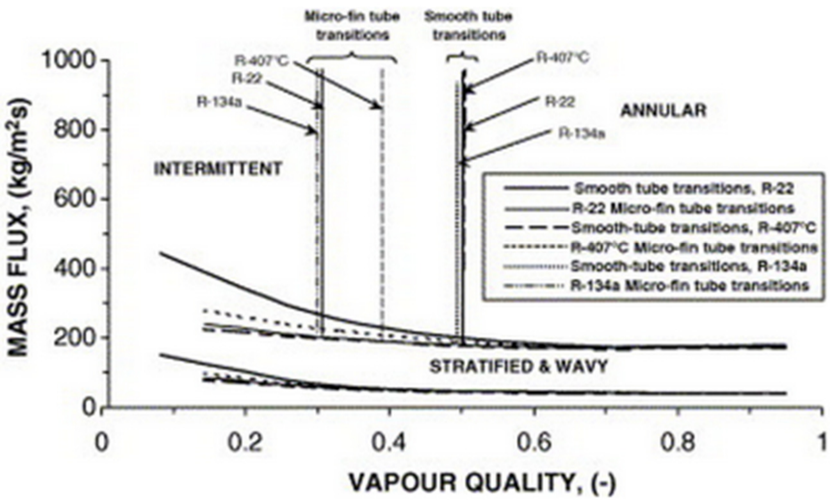

Figure 3. Flow pattern map for smooth and enhanced tube (Tube OD ≈ 9.5 mm) indicating how internal enhancement delays the transition of the flow from annular to intermittent, i.e., wavy and slug (Liebenberg and Meyer (2006))

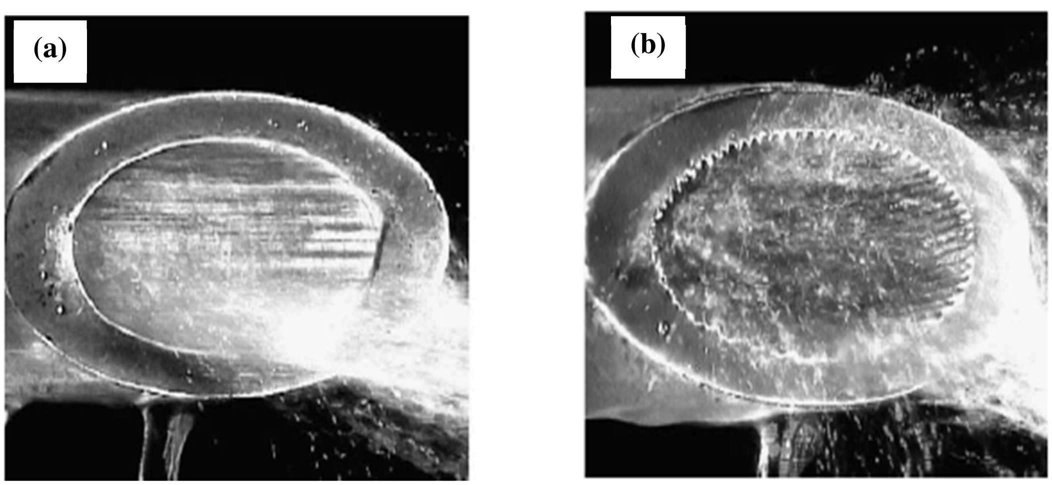

Figure 4. Influence of helical microfins on the flow pattern for (a) Smooth Tube – Stratified Flow Pattern; and (b) Microfinned Tube – Annular Flow Pattern (R134a, G=200 kg/m^2/s, x=0.5, T_s=40^{o}C, OD=8 mm, Cavallini et al. (2003))

INFLUENCE OF DIFFERENT PARAMETERS ON HTC AND PRESSURE DROP

Typically, internal tube enhancements improve the refrigerant side HTC but increase the pressure drop. The increase in HTC is captured in the form of the HTC Enhancement Factor (HTCEF) and the increase in pressure drop (ΔP) is captured in the form of the Pressure Drop Penalty Factor (PDPF). They are defined as follows:

$$\text{HTC Enhancement Factor} = \frac{HTC\ Enhanced\ Tube}{HTC\ Smooth\ Tube}$$

$$\text{Pressure Drop Penalty Factor} = \frac{\Delta P\ Enhanced\ Tube}{\Delta P\ Smooth\ Tube}$$

Helical Microfins

Helical microfins can achieve a HTCEF of the order of 3 with a modest PDPF of 1.5. Several factors influence the HTCEF, including tube diameter and vapor quality. Figure 5 illustrates the influence of vapor quality on the HTCEF and PDPF for tube diameters ranging from 3 mm to 9.52 mm. The HTCEF reduces with reducing vapor quality since the reduction in vapor quality is associated with transitioning from annular to stratified and wavy flow. Unlike the HTCEF, the vapor quality seems to have very little impact on the PDPF. For any given vapor quality, reducing the tube diameter reduces the HTCEF. This indicates that reducing the tube diameter reduced the efficacy of microfins in enhancing the HTC. In fact, one can see that for a 9.52 mm outer tube diameter at x=0.8, the HTCEF is approximately 3.1; this reduces to about 1.5 for a tube diameter as small as 3 mm. Reduction in the tube diameter also reduces the PDPF. For instance, compared to a 5 mm tube, the PDPF for a 3 mm tube is negligible. The inefficacy of microfins at smaller diameters could be because of the diminished centrifugal force and swirling as a result of the reduction in diameter.

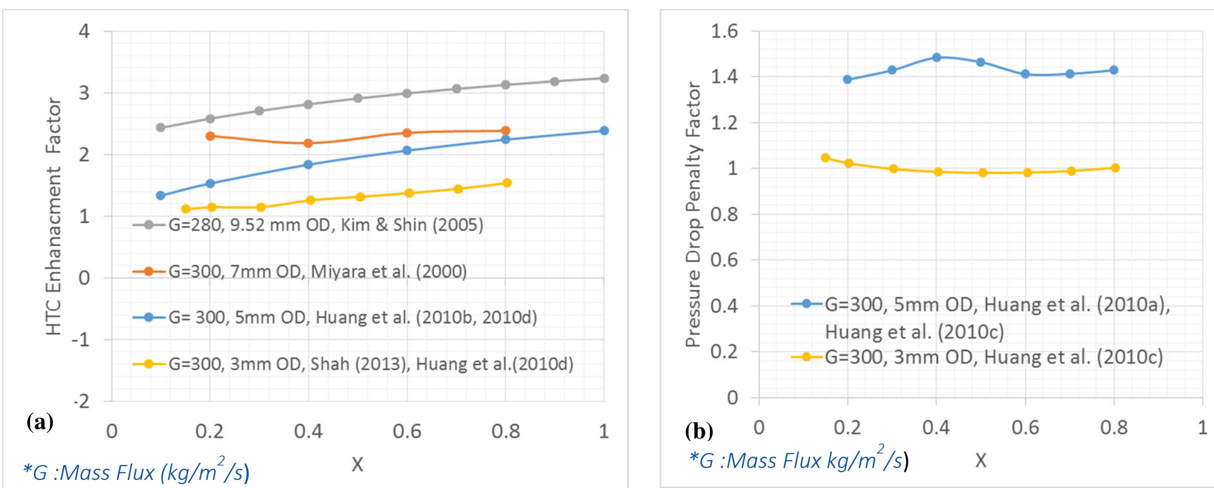

Figure 5. Influnce of vapor quality and tube diameter on (a) HTC Enhahncement Factor and (b) Pressure Drop Penalty Factor for helical microfinned tube.

Although the HTCEF for 3 mm tubes is the lowest (for those evaluated), this does not mean that smaller diameter tubes are inferior to larger diameter tubes for heat exchanger design and development. The HTCEF only addresses the impact of microfins on improving the performance of the corresponding smooth tube. In order to assess the benefit of small diameter tubes over larger diameter tubes, the absolute value of the HTC is important. The plots in Figure 6 address this issue. These results suggest that for smooth tubes, reducing the tube diameter increases the HTC. For microfinned tubes, the trend is not as straightforward. As compared to smooth tubes, however, microfinned tubes show less variation in the HTC due the change in tube diameter. For a given quality, the HTC for microfinned tubes is always higher than that for smooth tubes. This difference, however, is not as significant at lower qualities. A 3 mm smooth tube can approach the HTC of microfinned tubes at qualities less than x=0.4.

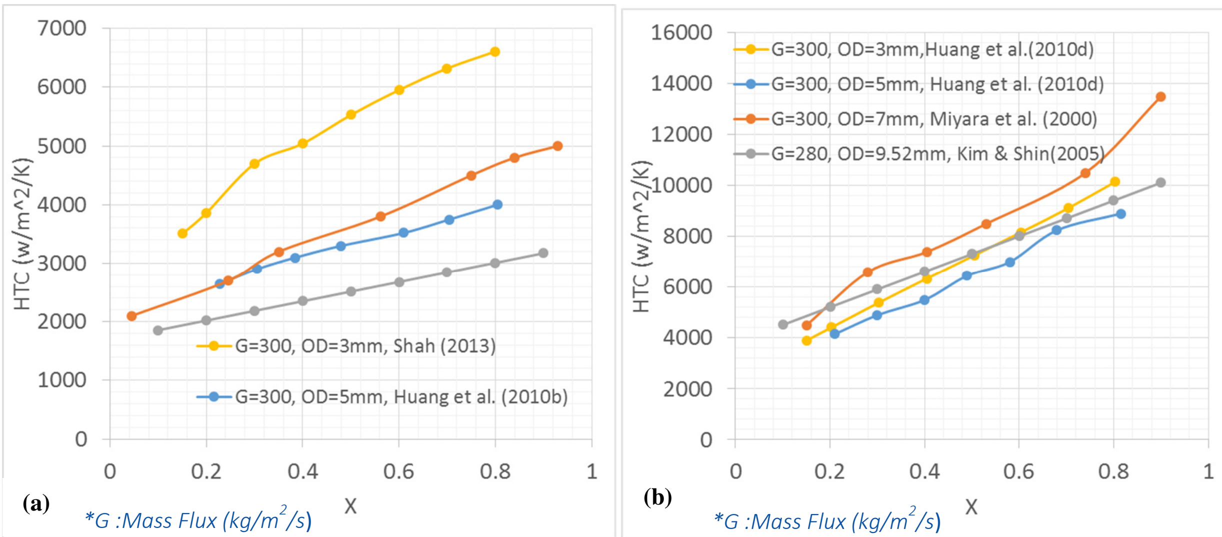

Figure 6. Influence if tube diameter on the HTC for (a) smooth tube ; (b) microfinned tubes.

The refrigerant mass flux also influences the HTCEF. In general, for very large mass flux flows, the HTCEF is lower than that for low mass fluxes (Cavallini et al. (2006)). While some researchers believe that for microfinned tubes, the HTCEF is a direct result of the increase in the heat transfer surface area. Per Cavallini et al. (2006), this is not entirely true. He showed that a microfinned tube with internal area enhancement factor 1.8 can have an even higher HTCEF, as high as 2.6, suggesting other factors may also be at play.

Herringbone Microfins

Herringbone fins are a recent addition as available internal microfin enhancements. Miyara and his coworkers (Miyara et al. (2003), Islam et al. (2007)) have performed extensive research on these fins. As per their work, at high mass flux (G = 300 kg/m^2/s, Figure 7b), herringbone fins can substantially outperform conventional helical fins. However, at low mass flux (G = 100 kg/m^2/s, Figure 7a), they may prove to be inferior.

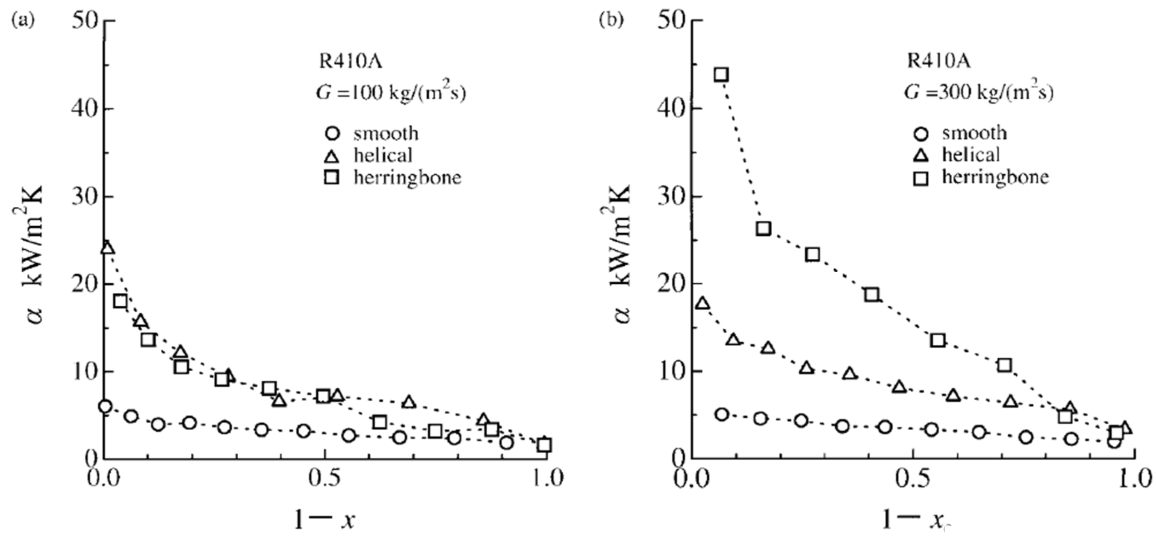

Figure 7. Comaprison of HTC for smooth tubes, helical microfinned tubes, and herringbone microfinned tubes for (a) small mass flux; and (b) large mass flux (All tubes had an OD =7 mm, microfin height and and width for both herringbone and helical-grove tube was almost identical. Miyara et al. (2000))

Microstructures

For sub-millimeter size tubes and channels, the effect of surface roughness has been explored by many researchers (Kandlikar et al. (2003), Yang et al. (2014), Wang et al. (2010)). Kandlikar et al. (2003) used an acid treatment to etch the tube surface and provide a desired surface roughness. Yang et al. (2014) used nano-wire bundles bonded to a Pyrex wafer through a micro-fabrication process to create a desired superhydrophilic surface. The effectiveness of microstructures is a result of the increased turbulence level and change in the surface tension properties. For boiling applications, these enhancements also facilitate nucleation. Kandlikar et al. (2003) showed a HTCEF of the order of 2 for tube diameters as small as 0.62 mm for single phase (water) flow. Yang et al. (2014) showed a HTCEF of the order of 2.5 for boiling deionized water using 250 µm microchannels. It is to be noted that microstructures are most effective for submillimeter size tubes; they lose their effectiveness for tube diameters greater than 1 mm.

IMPACT OF MICROFINS ON HEAT EXCHANGER DESIGN

In order to understand how microfins and the associated enhancement in heat transfer influences the design of the heat exchanger, an optimization study was conducted for a sample 3-ton condenser used for an air-conditioning application. The study included two optimization cases: a “baseline” heat exchanger with 5mm smooth tubes and an “enhanced” heat exchanger using 5mm microfin tubes. Table 1 lists the key parameters characterizing the study while Table 2 outlines the allowable variables used to develop optimum designs. Results from the optimization analysis show that for a given heat exchanger configuration (all of the same values for the parameters presented in Table 2, i.e. same tube length, fin spacing, etc.), the use of microfinned tubes results in a HTCEF between 2 and 3 over the smooth tube case, depending on the mass flux. The use of microfins increased the heat carrying capacity of the heat exchanger by as much as 21% and for certain configurations, the use of microfins was able to reduce the tube material up to 17%, the fin material up to 10%, and the airside pressure drop up to 11%.

Parameter	Value
Refrigerant	R410A
Inlet Pressure	403.2 psia (2.78 MPa)
Inlet Temperature	162.7^{o}F (345.76K)
Air Inlet Temperature	95^{o}F (35^{o}C or 308.15K)
Airflow Rate	2700 cfm (1.274 m^3/s), assuming uniform airflow

Table 1: Heat exchanger optimization study key parameters

Parameter	Value
Fins Per Inch	16, 18, …,28
Horizontal Tube Spacing (X tube OD)	1.5, 1.75, …3
Horizontal Tube Spacing (X Horizontal Tube Spacing)	1.0, 1.25, …2.25
Tubes per Bank	16, 20, 24, …,48
Tube Banks	1, 2
Tube Length (m)	1.25, 1.5, 1.67, …2.25

Table 2: Heat exchanger optimization study variables

Figure 8 shows the results used to identify heat exchanger configurations optimized for minimum air side pressure drop. Each red point on the graph indicates a heat exchanger design meeting the following requirements:

- Heat capacity > 13 kW
- Air side Pressure Drop < 18.45 Pa
- Degree of sub cooling = 5.8°C
- Coil face area $\cong 1.135\ m^2$

The blue points represent the Pareto curve, or optimized designs. Table 3 summarizes the details of the heat exchanger designs with the lowest air side pressure drop (highlighted by a circle) from each of these plots. The results indicate that microfins can result in an 11% reduction in air side pressure drop accompanied by 5%-6% savings in the tube and fin material mass, without changing the capacity of the heat exchanger.

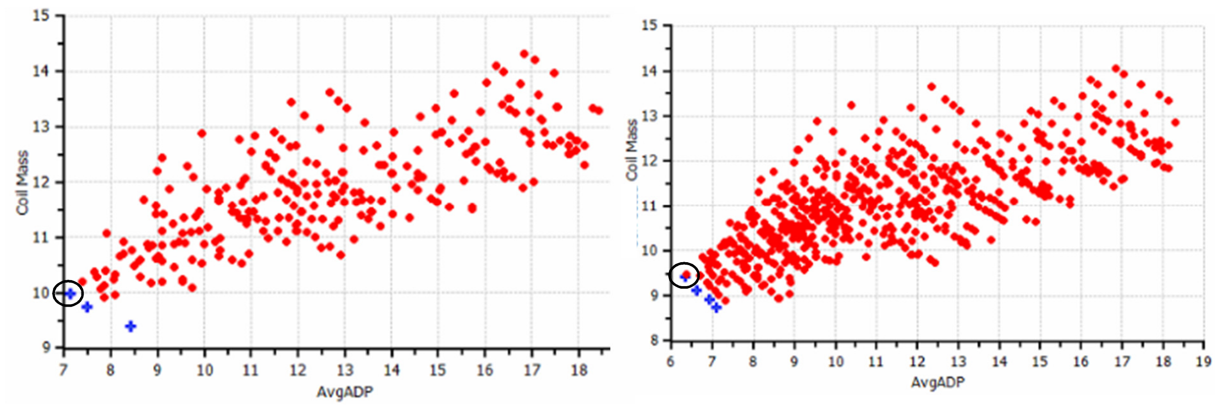

Figure 8. Optimization (with respect to air side pressure drop) study for 5 mm (a) smooth tube; (b) microfined tube.

	Smooth Tube	Microfinned Tube	% Change
Heat Capacity (kW)	13.0	13.1	0%
Air Pressure Drop (Pa)	7.1	6.3	-11%
Tube Mass (kg)	4.6	4.3	-5%
Fin Mass (kg)	5.4	5.1	-6%
Coil Mass (kg)	9.9	9.4	-6%

Table 3: Comparison of the minimum air side pressure drop case for smooth tube and microfin tube heat exchangers.

MANUFACTURING CHALLENGES

Microfin tubes are currently manufactured using a mechanical expansion process. As tube diameter decreases, the difficulty in manufacturing microfin enhanced tubes and heat exchangers increases. Herringbone microfins are considerably harder to manufacture, requiring a rolling and welding process to incorporate the relatively complex geometry that is labor and cost intensive. Microstructures require completely different manufacturing processes, as outlined above, but have not been shown to be effective for tubes larger than 1 mm OD. Present tube and heat exchanger development and research is relatively limited by the mechanical processes required to make internal tube enhancements.

Burr Oak Tools has developed a new manufacturing process using pressure expansion to form the enhanced tubes. Whereas mechanical expansion has the potential to deform the internal enhancement, pressure expansion offers the opportunity to create complex and relatively fragile geometries. With this methodology in place, new enhancements can be explored to identify additional enhancement geometries capable of significantly increase heat transfer performance.

CONCLUSION

The present document briefly reviews research highlighting various internal tube enhancements and their effect on heat transfer coefficient (HTC). The document especially focuses on helical microfin enhancements used for condensation applications. Although reducing the tube diameter increases the HTC for smooth tubes, the effectiveness of helical microfins diminishes as the tube diameter reduces. The improvement microfins can offer for a heat exchanger assembly, however, specifically for 5mm tubes, can be relatively significant. An optimization study revealed that as compared to 5mm smooth tube heat exchangers, the 5mm microfinned tube designs can increase heat capacity by as much as 21% or reduce the air side pressure drop by as much as 11%, the tube material mass by as much as 17%, and the fin material mass by as much as 10%. Other internal enhancements, such as herringbone fins and surfaces with microstructures, are still under development. How effective these alternatives are as compared to helical fins for comparable condensation applications requires additional research.

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