Copper Development Association Inc.
Copper Alliance

Surface Enhancements Inside Copper Tubes Improve the Heat Transfer

Microfins Increase the Efficiency of Heat Exchangers

The trend for at least the past twenty years has been toward smaller-diameter copper tubes, which are advantageous in many respects:

Firstly, the internal heat transfer coefficients (HTCs) are higher for smaller diameter tubes, offering an immediate payback because less tube material and less refrigerant are required to provide the same capacity, whether for the evaporator or the condenser. This increase in HTC is based on the surface-to-volume ratio, which is higher for smaller diameter tubes, as described elsewhere [1].

Secondly, the smaller diameter tubes can allow for more efficient, streamlined airflow outside the tubes, as shown in simulations.

Thirdly, a given tube wall thickness can support higher pressures for smaller diameter tubes, meaning tube walls can be made thinner, resulting in even less material usage and lighter weight.

Yet, tube diameter is not the whole story. Another factor is the inside surface of the refrigerant tube. This surface can be smooth, or it can be modified with geometrical features that enhance heat transfer.

Flow Patterns

Basic principles of fluid dynamics and convective heat transfer demonstrate that the local heat transfer coefficient (HTC) is dramatically affected by the pattern of the flow of the refrigerant as it passes through the tube. The flow pattern can be laminar or turbulent. A laminar flow is smooth and streamlined. A turbulent flow is irregular and chaotic. The transition from laminar to turbulent flow depends on the Reynolds number (Re). https://en.wikipedia.org/wiki/Reynolds_number

Osborne Reynolds (1842- 1912) spent his career at what is now the University of Manchester. He studied heat transfer between solids and fluids, bringing about improvements in boiler and condenser design. The Reynolds number is affected by the fluid's density, viscosity, and velocity. It is also affected by the roughness or irregularities on the surface. A smooth surface contributes to a low Reynolds number, favoring laminar flow. An enhanced surface contributes to a high Reynolds number, favoring turbulent flow.

Another way of understanding fluid flow patterns is in terms of a boundary layer. Close to the surface, the fluid velocity is zero. The velocity gradually increases further from the surface. A “boundary layer” can be defined close to the surface if the flow direction is represented as straight lines. With respect to heat transfer, this boundary layer acts as an insulating layer because it inhibits convective heat transfer. Instead, heat must be transferred by conduction through the boundary layer. As is well known by anyone who has ever felt a cool breeze on a hot summer day, convection cooling is much more efficient than cooling by thermal conduction. (Figure 1.)

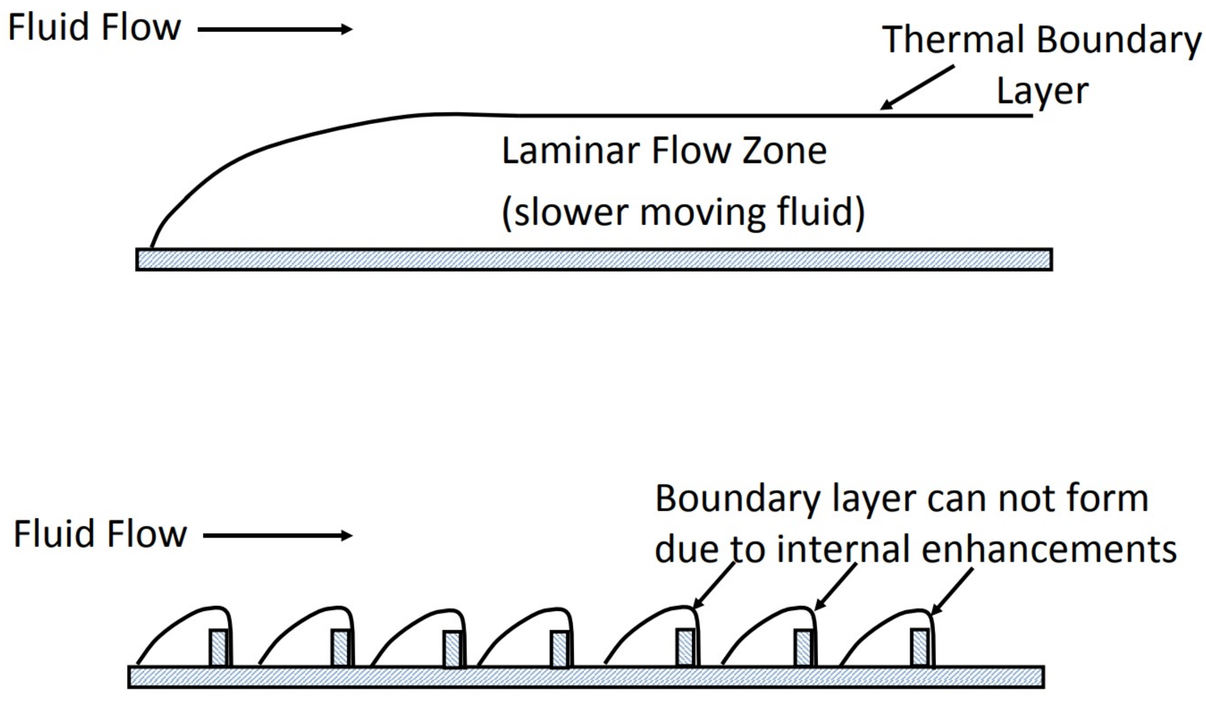


Figure 1 – Laminar flow through a tube with smooth inside walls produces a thick boundary layer, which inhibits convective heat transfer perpendicular to the tube wall (top). Microfins disrupt the boundary layer and promote heat transfer by convection. (bottom).

Turbulence is a good thing for evaporation and condensation inside copper tubes. It increases the local heat transfer coefficient (HTC) inside tubes. Irregularities on the inside surface of tubes interrupt the straight-line paths of refrigerant. When one of these lines collides with an obstruction or impediment on the surface, the refrigerant suddenly must change directions. Also, the leeward side of the obstruction creates a slight vacuum, further disrupting the flow pattern.

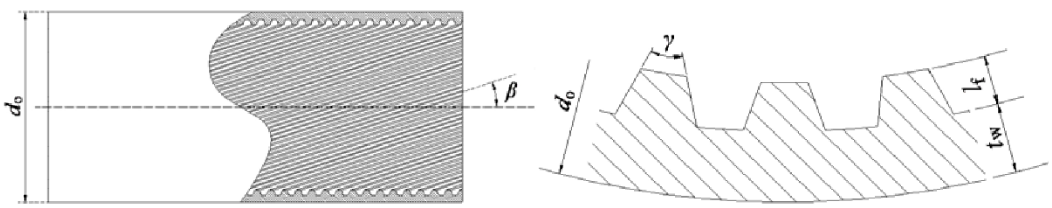
Local HTCs vary with the physical properties of the refrigerant as well as the fluid's velocity, temperature, and pressure. HTCs also depend on vapor quality, which is the ratio of vapor mass to total mass. The vapor quality is represented by the Greek lowercase letter chi (χ) or the letter “x.” A vapor quality of zero ($\chi = 0$) is a saturated liquid. Such a 100 percent liquid refrigerant might be found at the exit manifold of a condenser coil. A vapor quality of one ($\chi = 0$) might be found at the exit manifold of an evaporator coil.

The Geometry of Microfins

In the case of inner grooves or microfins for tubes, the grooves have widths on the order of hundreds of microns at the top of the groove. It is remarkable that these inner grooves can enhance the HTCs by as much as 300 percent, depending on the tube diameter, the flow rate, the refrigerant, and the type of enhancement. The variability in HTC enhancement has spurred competition among tube suppliers, who are the experts in fabricating tubes with various kinds of enhancements, for example, herringbone or helical patterns.

Today, tube manufacturers can vary the features of microfins in many ways. They can vary the width at the top of the groove. They can vary the depth of the groove. They can vary the groove wall angle, the helical angle, and the spacing between the grooves.

Nowadays, the number of tube enhancements has proliferated to such an extent that it is necessary to work closely with tube suppliers to optimize the configuration for any given application. The performance of these tubes must then be correlated with laboratory experiments for specific refrigerants, flow rates, pressures, and quality factors. Tube suppliers working with research labs can provide the necessary correlations to allow for accurate predictions of the efficiency gains that can be realized using inner-grooved smaller-diameter tubes.



(a) Cutaway view of the test tube

(b) Cross section of fin

5 mm O.D. microfin tube:
$\beta = 18°$;
$\gamma = 40°$;
$t_w = 0.20$ mm;
$l_f = 0.14$ mm;
$n_f = 40$.

4 mm O.D. microfin tube:
$\beta = 12°$;
$\gamma = 40°$;
$t_w = 0.22$ mm;
$l_f = 0.12$ mm;
$n_f = 40$.

Figure 2 –Typical geometry of microfins, i.e., enhancements made to the inside surfaces. [2]

Tube Correlations

Clearly, the heat transfer coefficient (HTC) is different for condensation than for boiling. It will depend on the vapor quality and temperatures at different locations as the refrigerant travels through the copper tubes of the evaporator or the condenser. Calculating HTCs and flow patterns from first principles is an intractable problem, especially for turbulent flow patterns; however, laboratory experiments on copper tubes allow the local HTCs to be modeled quite accurately.

There has been an increase in research papers on smaller-diameter copper tubes commensurate with their use in household appliances and commercial equipment. There is no substitute for experimentally measuring heat-transfer coefficients and pressure drops for various tube sizes, refrigerant mixes and microfin geometries. Data from these experiments can then be used in simulation software to predict the performance of heat exchangers with high accuracy. Conventional models often do not apply to smaller diameter tubes; hence, there is a need for new experiments.

University Research on Microfins

The academic literature refers to the inner grooves of copper tubes as ”microfins.” For example, at the 2018 Herrick Conferences at Purdue University, several papers on smaller-diameter copper tubes were presented in a technical session on “Heat Transfer in Microfin Tubes and Microchannels.” [3]

The experiments from the Tokyo University of Marine Science and Technology (TUMSAT) were especially intriguing because they showed the combined effects of flow rates and microfin geometry on heat transfer coefficients and pressure drops (Papers 2542 & 2511). As the refrigerant evaporates along the length of a tube, distinct flow types could be identified. Paper 2511 helps us understand how the optimal tube enhancements may differ for different flow rates and types.

Paper 2469 from Padova University reported on R1233zd(E) and R245fa flow boiling heat transfer and pressure drop inside a microfin tube.

An excellent paper from Nagasaki University and the Research Center for Next Generation Refrigerant Properties (NEXT-RP) at Kyushu University measured heat transfer and pressure drop of R1123/R32 flow in horizontal microfin tubes during condensation and evaporation (ID 2164).

Two additional papers from Padova University (ID 2204 and ID 2205) examined the behavior of low-GWP refrigerants inside smaller-diameter copper tubes for flow boiling and condensation, respectively.

The refrigerants tested are reflective of the large number of papers dealing with new low-GWP refrigerants in general and HFO blends in particular. Many academic presentations open with an overview of the timetables for the phase-out of high-GWP refrigerants as required by the Kigali agreement and European F-Gas legislation.

Research from Burr Oak and OTS

A white paper prepared by Optimized Thermal Systems and Burr Oak Tool Inc. reviews the enhancements available for tubes of different tube diameters, from 9.5 mm to 5 mm and smaller [4].

This joint research by OTS and BOTI, sponsored by the Copper Alliance, correlated surface enhancements with enhanced HTC values and reduced pressure drops. These values have already been precisely measured for commonly used surface enhancements and, in many cases, have been included in the industry-standard software for designing heat exchanger coils.

Daniel Bacellar and Dennis Nasuta from OTS delivered a webinar that explains the use of these new correlations in the CoilDesigner software [5]. For those interested in learning the “nuts and bolts” of how CoilDesigner works with fin and tube correlations, the webinar titled “The Advantages of Small Diameter Copper Tube-Fin Heat Exchangers” is recommended. It is the first in a series of six webinars promoted by OTS with the Copper Development Association (CDA). An early paper on CoilDesigner® was published in 2002 [6]. Other key papers from CEEE were published in 2006, 2008, and 2009 [7-9].

Microfins at the International Congress of Refrigeration (ICR)

Research on tube correlations continues to flourish. At the ICR 2023, Technical Session 25 on Condensation, chaired by Professor Giulia Rhigetti of the University of Padova, included four papers on experimental measurements of HTCs on new refrigerants and refrigerant blends [10].

A paper titled “Principles of evaporator coil design for air source cold climate heat pumps using smaller diameter copper tubes and low GWP refrigerants” was presented in Technical Session 36 on Heat

Exchangers at the ICR. Among other topics, the effects of microfins and wall thickness were reviewed in the case of 5 mm copper tubes [11].

Simulations were performed on a simple heat exchanger using the correlations available for four types of enhancements as well as three wall thicknesses for smooth tubes. Table 1 shows the variation in heat exchange capacity as the tube thickness and internal surface enhancement were varied.

These simulation results suggest that tube wall thickness has little effect on the capacity of smooth tubes. They also show a difference between smooth tubes and microfinned tubes. As mentioned above, these differences must be interpreted with caution for evaporators operating at low ambient temperatures. The inside-the-tube heat transfer coefficient (HTC) is dependent upon the phase of the refrigerant and the pressure of the vapor as it travels through the tubes.

Table 1. Effect of inside tube enhancement on capacity*

Inside Tube Enhancement (HXSim ID)	Tube Outer Diameter (mm)	Tube Wall Thickness (mm)	Microfin Height (mm)	Capacity (kW)	Airside Pressure Drop (kPa)
4	5	0.2	0.15	3.438	25.7
5	5	0.21	0.14	3.367	25.7
6	5	0.23	0.12	3.486	25.7
7	5	0.25	0.15	3.407	25.7
8	5	0.23	0	2.609	25.7
9	5	0.28	0	2.688	25.7
10	5	0.3	0	2.724	25.7

*Adapted from Table 3 Shabtay *et al.* [11].

Noninvasive Pressure Expansion

Noninvasive pressure expansion technology from Burr OAK Tool of Sturgis, Michigan, incorporates a proven technology of tube expansion to join the tube and fin. Precisely controlled pressure is used to expand tubes for an interference fit between the tubes and fins.

The method of using pressure to expand tubes is not completely new. It has been used in the hydroforming industry, where containment for the final tube shape is determined with dies that encapsulate the material.

In the case of expanding inner-grooved copper tubes into fins, pressure expansion offers several advantages. One major advantage is that pressure expansion is inherently a zero-shrink process. Equations describing plastic flow in material show that a tube experiences zero lateral strain while pressure is applied to expand the tube diameter plastically. In effect, the internal pressure that causes hoop stress in the tube, resulting in expansion of the tube diameter, also places tension on the tube in the precise amount needed to prevent the tube from shrinking.

Another significant advantage of using pressure to expand tubes is that the internal tube enhancements are not disturbed as they are when using a mechanical bullet. This comparison is illustrated in images of internally enhanced tubes. For the bullet method, the stresses exerted on the internal enhancements of the tube are significant. The bullet method could deform the tops of fragile types of inner fins. Expanding tubes with pressure enables tube manufacturers and researchers to explore new designs of surface enhancements.

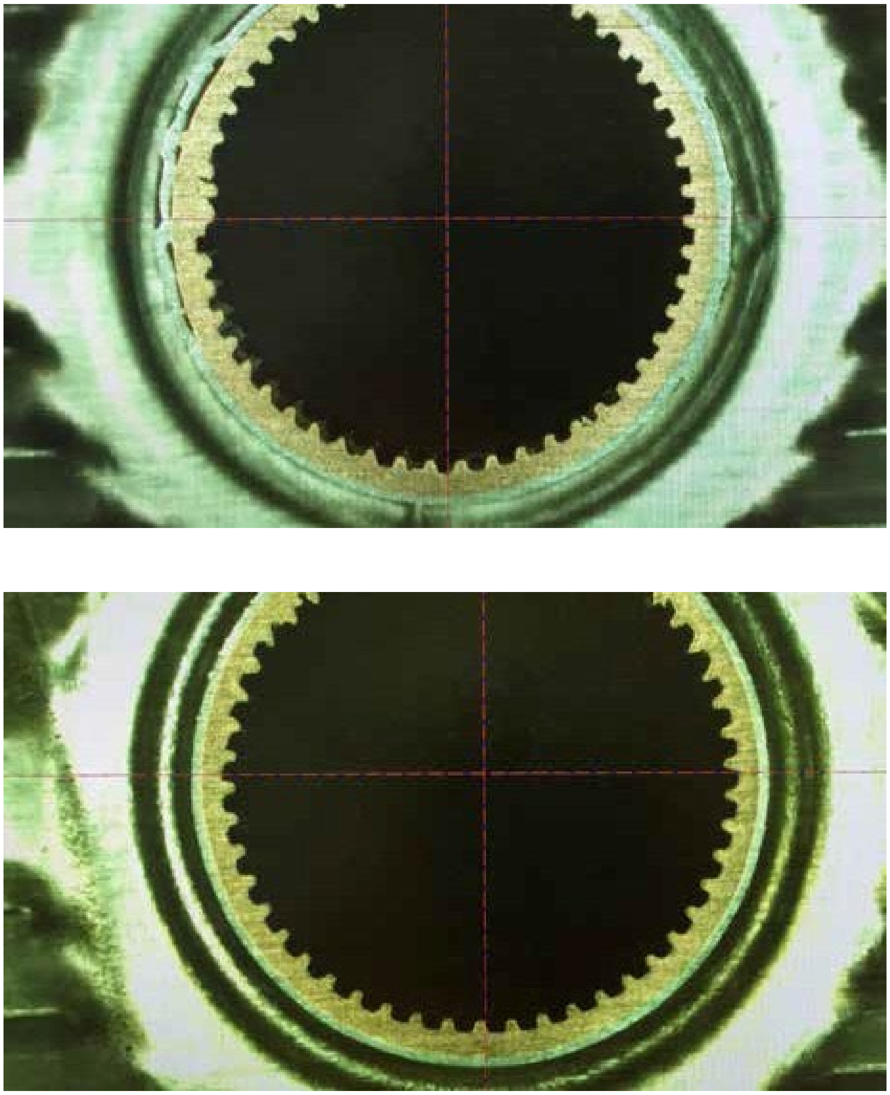


Figure 3 – Bullet expanded tube (top) and pressure expanded tube (bottom). Courtesy of Burr OAK Tool Inc.

Conclusion

The use of inner-grooves and surface enhancements is standard practice in heat exchangers for RACHP appliances and equipment. The gains in heat transfer efficiency are too great to ignore and the technology is widely available from tube suppliers. Expect more research and innovations as even smaller diameter tubes are employed in a new generation of RACHP products using low-GWP refrigerants and refrigerant blends.

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