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Building Better Appliances with Smaller-Diameter Copper Tubes

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The "less is more" principle popularized by American inventor R. Buckminster Fuller is especially apt with respect to coil designs for air-conditioning and refrigeration appliances. Demands to increase energy efficiency and lower material costs forces manufacturers to reconsider their coil designs. Also, concerns about the atmosphere are driving manufacturers to reduce refrigerant volumes and minimize the ozone depletion potential (ODP) and global warming potential (GWP) of refrigerants.

Ten years ago, the design and manufacture of round-tube, plate-fin (RTPF) coils already was a mature technology in many ways. Fin patterns had been thoroughly researched, meticulously modeled and fully optimized. Furthermore, the inside walls of copper tubes had been enhanced in various innovative ways to improve the heat transfer inside-the-tube. There was little room for incremental improvement except for one key design feature: the tube diameter.

With regard to the effect of tube size on heat transfer, less is more. Of course, this is not a new discovery. The principle has been used by living organisms throughout history. Capillaries are very effective in cooling the body. In that case, warm blood is the heat transfer fluid, which is pumped to the skin surface where heat can be removed by the evaporation of sweat. The smallest blood vessels are only 5 to 10 micrometers in diameter!

The March to Smaller Tubes

Yet when the industry first conceived of using smaller diameter copper tubes, the challenge appeared daunting.

The Carrier Corporation dubbed its initiative "Everest," an intense 18-month project culminating in the introduction of a new line of air-conditioning products in January 2006 [1]. The new products used 7-mm copper Microtube™ coils, which significantly reduced the size of the new units. The company garnered several manufacturing awards in 2006 and received prestigious *Consumers Digest* "Best Buy" awards as well for several of these products.

The march to smaller diameter copper tubes had begun.

Similarly, Goodman announced its new SmartCoil™ technology in 2008. In this case, the coils were made of aluminum fins and 5-mm copper tubing. Rusty Tharp was one of the team members involved in the development of SmartCoil products when the project began in 2007. He currently is the Director of Regulatory Affairs, Goodman Manufacturing Company, a member of the Daikin group.

"Many new manufacturing methods were pioneered in the development of the first coils with 5-mm copper tubes," explained Tharp. "Five millimeter copper tubes are now used by Goodman for central air conditioners in the 1.5 ton to 15 ton capacity range. Our copper supplier willingly worked with us to facilitate the transition to smaller diameter copper tubes. Finding the optimal mix of performance and product size is important to being a competitive player in the HVAC market, which is why Goodman has chosen 5-mm SmartCoil condenser coils as the

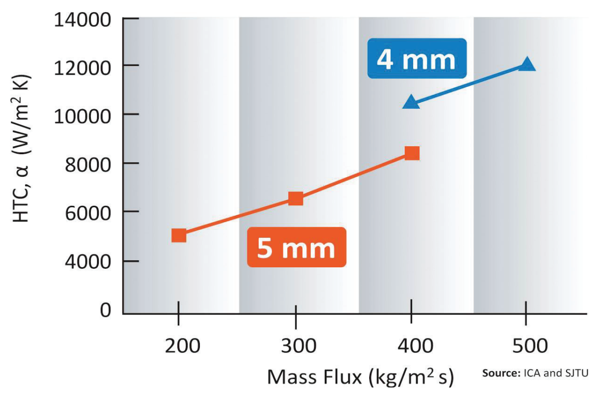

Figure 1. The local heat transfer coefficient increases as tube diameter decreases, which means more heat can be transferred using less coil material if the smaller tube diameters are used in coil designs.

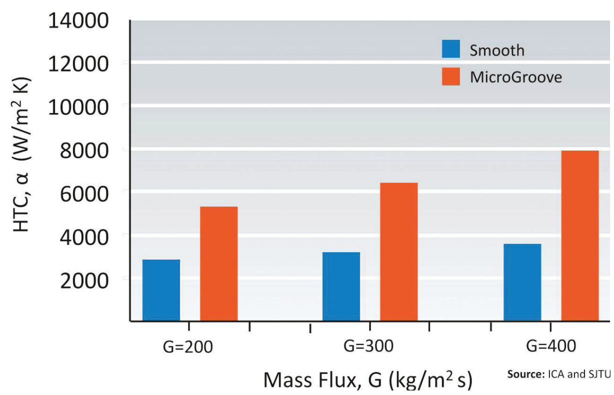

Figure 2. Inner grooves or "microfin" patterns can further improve the local heat transfer coefficients. (Data is from laboratory measurements on 5-mm diameter copper tubes with and without inside-the-tube surface enhancement.)

foundation for our cooling products." Condenser coils made from 5-mm diameter copper tubing are manufactured in Houston, Texas and Fayetteville, Tennessee. According to Tharp, the key benefits for the customer are reduced refrigerant volume, energy efficiency, compactness and ease of maintenance.

"Reduced refrigerant volume is good for HVAC products because, as a general rule, systems with lower refrigerant charges have lower failure rates," he explains. "The 5-mm diameter copper tubes allow for energy-efficient comfort products and reduce the size and weight of these products. Furthermore, SmartCoil condenser coils are easier for our customers to service in the event of a leak. Industry technicians are familiar with copper as compared to aluminum microchannel heat exchangers. The latter can be difficult, if not impossible, to repair in the field where conditions are less than optimal."

A Research Consortium

Meanwhile, a consortium to further develop the technology of smaller-diameter copper tubes was formed in China. The consortium is a model of industry cooperation. Major ACR manufacturing giants such as Chigo, Gree, Haier, Kelon and Midea collaborated with tube suppliers via the International Copper Association. Participating research institutions included the School of Energy and Power Engineering at Xian Jiao Tong University (XJTU) and the Institute of Refrigeration and Cryogenics at Shanghai Jiao Tong University (SJTU).

The consortium's initial focus was on the use of smaller diameter copper tubes in room air conditioners, including window units and ductless split systems. In the highly competitive business of home appliances, any improvement in efficiency or reduction in materials can be a major competitive advantage. The smaller diameter copper tubes offered major advantages in both respects.

The research included simulations of coil designs, laboratory measurements of tube properties, the development of software design tools and the construction of prototype designs as well as modifications of manufacturing equipment and processes.

Laboratory Confirmation

The "less is more" principle was confirmed in the laboratory in a beautiful series of experiments by Professor Guoliang Ding and his colleagues and students at SJTU. They measured the local heat transfer coefficients (HTCs) inside the tubes and found that the HTCs were significantly increased by reducing the tube diameters [2, 3].

The results are as predicted by theoretical models pertaining to heat transfer. In a condenser tube, for example, the heat energy moves outward through the flowing refrigerant; and across the insulating boundary layer of the slowly moving refrigerant near the inside surface of the tubes. Figure 1 shows the increase in the local heat transfer coefficient as the tube diameter is decreased. These results show how more heat can be transferred using less coil material by making the tubes smaller.

Inner Grooves

Furthermore, experiments show that even for tube diameters of 4-mm or less, inner grooves or "microfin" patterns can further improve the local heat transfer coefficients. Figure 2

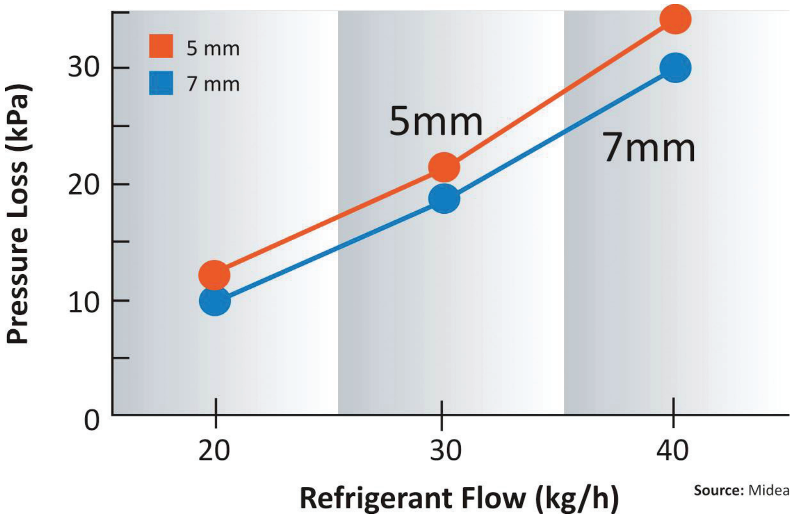

Figure 3. A smaller diameter tube results in a higher pressure drop for a given flow rate of refrigerant through the tube.

shows how inner grooves increase the local heat transfer coefficient in small diameter copper tubes.

The exact patterns of the inside tube surface enhancement remains a subject of intense research. Tube supplier members of the ICA have developed proprietary enhancements, which can bust up insulating boundary layers in condensers or speed up nucleation of vapor bubbles in evaporators. The most effective patterns are application specific.

ICA refers to the technologies associated with smaller diameter, inner-grooved copper tubes as MicroGroove™ technology, which is suggestive of a “micro” (small diameter) tube with “grooves” (i.e., surface enhancements or “microfins”) on the inside surfaces of the tubes. The term can also be applied to coils, meaning such coils contain MicroGroove copper tubes.

Cross Sectional Area

The smaller cross sectional area of a MicroGroove tube affects the flow rate and pressure drop through the individual tubes as shown in Figure 3. A smaller diameter tube results in a higher pressure drop for a given flow rate of refrigerant through the tube.

For this reason, not all ACR applications are candidates for smaller diameter tubes. Conventional copper tubes with diameters of 3/8 inch (9.52 mm), 5/8 inch, 1 inch or larger will continue to be used in many applications, especially where high flow rates take precedence over heat transfer coefficients.

Fortunately, in the case of room air conditioners, the higher pressure drop can be readily accommodated by modifying the tube circuitry.

Tube Circuitry and Fin Designs

Pressure drops can be reduced by increasing the number of paths through the heat exchanger and shortening the length of each path. In other words, the tube circuitry can be adjusted to increase the

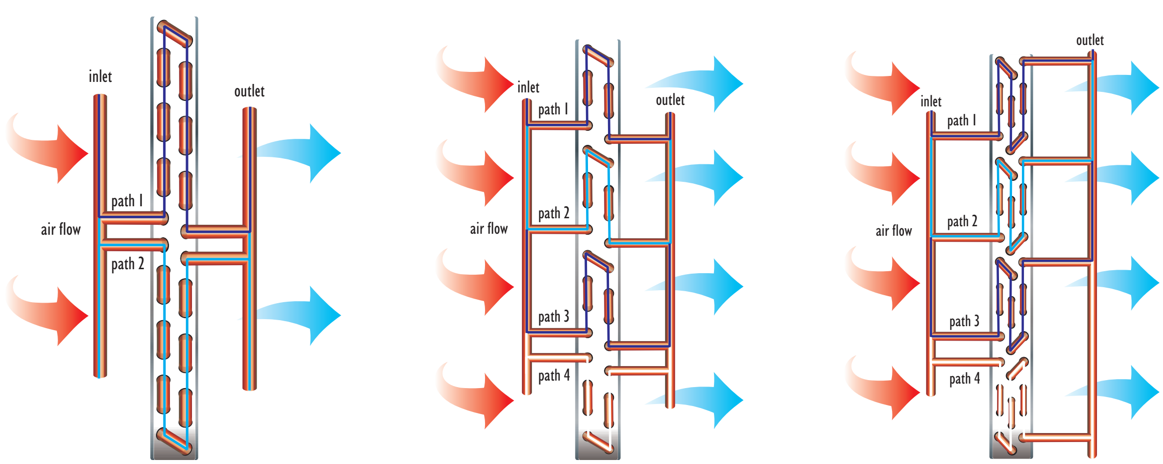

Figure 4. Tube circuitry can be adjusted to accommodate smaller diameter tubes.

overall flow rate through the coil. The search for an optimized circuitry is typically guided by a knowledge base, which focuses the simulation trials on designs that can be readily manufactured.

Figure 4 shows a simple example of how the tube circuitry can be adjusted to accommodate smaller diameter tubes.

Fin optimization should not be overlooked in the design of new coils. The optimal fin design for smaller diameter tubes can be quite different than a fin design optimized for conventional tubes. Note that smaller diameter tubes have less “form drag” than larger diameter tubes. Hence, all other factors being equal, MicroGroove coils can be made more streamlined and more efficient than conventional coils with respect to outside-the-tube heat transfer. That is why it is important to reconsider and re-optimize fin designs when switching to smaller tubes. Conventional fin types may no longer be optimal.

The effect of tube circuitry and fin design on coil performance has been accurately modeled and optimal configurations can be identified using latest coil-design software tools. When verified by building prototype coils and measuring actual performance in laboratory experiments, the results of such simulations today agree with actual coil performance to a high degree of accuracy, typically within one percent.

Nowadays, given accurate heat transfer coefficients, these simulations can speed up the process of optimizing the coil circuitry and fin designs. Several papers have been published on this topic by members of the research consortium [4-6] as well as in the trade media [7-8].

Rusty Tharp from Goodman also reports that pressure drop was controlled by appropriately choosing the number of refrigerant paths (circuits) in each condenser coil. “The aluminum fins themselves were obviously changed due to the design and spacing of the smaller-diameter copper tubes. Heat transfer was optimized by selection of appropriate aluminum fin enhancements,” he says. “Goodman uses computer simulations in all of its product designs.”

Manufacturing Methods

Once the “less is more” principle was demonstrated in the laboratory, OEMs were highly motivated to develop the necessary high-volume manufacturing methods.

It is fortuitous that familiar manufacturing techniques can be used with the smaller diameter tubes. The equipment and techniques are modifications of the equipment used to manufacture coils with conventional tubes. Manufacturing processes include the following:

Figure 5. A non-shrinkage tube expander made by the Zhongshan OMS Industrial Company is used in the production of heat exchanger coils with smaller-diameter copper tubes for residential applications.

- *Fin Stamping,* which includes a progressive fin die for producing fin patterns in sheets of aluminum or copper
- *Tube Processing*, which includes Hair Pin Bender, a Straight Tube Cutoff and a Return Bend Production
- *Handling & Assembly,* which includes processes for stacking fins and lacing arrays of tubes through the fins
- *Expansion,* which provides tube-to-fin contact

Smaller diameter tubes require better control over the manufacturing tolerances for each of these steps. The quality of the tube materials may also be more important for manufacturing processes involving smaller diameter tubes; equipment modifications and in some cases new equipment may be needed. Nevertheless, the processes and equipment will be familiar to coil makers.

The above equipment is illustrated and described in the MicroGroove webinar titled “The Manufacture of ACR Coils with Smaller Diameter Copper Tubes” hosted by *appliance DESIGN* and the *ACHR News* March 2012. A recording of the webinar is now available on YouTube and the slideshow and script can be downloaded from the “Webinar” section of microgroove.net.

New hairpin benders, fin dies and expanders and their associated components were procured by Goodman to allow for volume production of the new coil designs. “Lacing long, small hairpins was initially a challenge and expanding such long coils with small diameter tubes without bending expander rods also presented several challenges,” says Tharp. “Changing the sheet metal cabinetry and coil manifolding were among the most challenging aspects of converting designs from 3/8" diameter copper tubing to 5-mm SmartCoil copper tubing. These challenges were met successfully. We now have a manufacturing process that is reliable and flexible with regard to our product mix."

Non-Shrinkage Tube Expander

In a typical coil manufacturing process, tubes are expanded by pushing a "bullet" that is slightly larger in diameter than the tube through the entire length of the tube. The purpose of the expander is to ensure that the tubes are in firm contact with the fins.

Tube expansion occurs with an increase in the circumference. For a constant volume of copper tube material, geometrical considerations demand that tube expansion be accompanied by a decrease in tube length or reduction in tube wall thickness. If the tube length is held constant then the material is made up by slightly decreasing the tube wall thickness. Otherwise it is made up by reducing the overall tube length.

For window type ACs and split units (ductless systems), OEMs have reported variations of tube lengths after the tube expansion step. The lack of control over the final lengths of tubes after the tube expansion step in some cases can disrupt later automated assembly steps, such as the attachment of return-bends to the open tube ends.

Several OEMs have solved this problem by using a non-shrinkage tube expander, which holds the tubes length constant during the expansion process, hence the term "non-shrinkage" tube expander. One type of non-shrinkage tube expander is made by the Zhongshan OMS Industrial Co., Ltd.

Figure 5 shows a non-shrinkage tube expander currently used in the production of residential heat exchanger coils. For comparison, Figure 6 illustrates a tube expander from Burr OAK Tool Inc. In the latter case, the tubes are vertically oriented as bullets are passed through the tubes.

Not all OEMs are using a non-shrinkage tube expander. Some are finding other ways to expand the tubes and/or cope with the differences in tube lengths.

Burst Pressure

One advantage of smaller diameter tube is that the burst pressure of the tube increases as the diameter decreases if the tube thickness is held constant. This fundamental relation comes from basic pipe design theory and is a bonus for users of MicroGroove. Consequently, tube wall thickness can be reduced, which results in further materials savings. Reduced tube wall thickness also reduces the amount of force required to expand the tubes.

For some refrigerants, the refrigeration cycle necessitates the use of higher pressures and hence higher burst strengths for the tubes. An extreme example is the use of R744 as a refrigerant. For the transcritical R744 refrigeration cycle, the carbon dioxide may be compressed to 100 atmospheres of pressure or more. Here a higher burst pressures is a necessity! Fortunately, with smaller diameter copper tubes, such high pressures are readily managed.

Tharp reports that the burst strength of the 5-mm SmartCoil copper tubing used by Goodman is higher than the burst strength of 3/8 inch diameter copper tubing.

Antimicrobial Coils

Another development in coil manufacturing is the increased interest in all-copper coils. The reason for the heightened interest is the recognition that copper is inherently antimicrobial. There is no need to coat copper tubes to benefit from the antimicrobial properties of copper. All that is necessary is to use copper fins and copper tubes.

Bacteria can thrive on materials such as aluminum or stainless steel, which have no measured antimicrobial properties. Evidently

Figure 6. This vertically oriented tube expander made by Burr OAK Tool Inc. was specially designed for the expansion of 5-mm diameter tubes.

the bacteria can form layers on these materials and become a substrate for further growth of microorganisms. However, on copper surfaces, the growth of bacteria, mold and mildew is quickly suppressed as a result of the antimicrobial properties of copper, so the surface is cleaner and easier to maintain.

The increased thermal conductivity of the MicroGroove tubes pairs well with the high thermal conductivity of copper fins, allowing for more compact antimicrobial coil designs and reducing the weight of the coils.

Official endorsement of research conducted by the Copper Alliance was received via the US Environmental Protection Agency "Treated Article Exemption" registration for copper alloys in HVAC applications. Granted in September 2010, the registration allows copper HVAC components to make product protection claims in the US. These products can claim to suppress the growth of bacteria, mold and mildew that reduce system efficiency and cause product deterioration or foul odors.

Looking Ahead

What does the future hold for even-smaller-diameter copper tubes in appliance design and manufacturing? "If further improvements can be discovered with regard to optimization of heat transfer, less refrigerant use and more compact sized units, we plan to actively explore all options," says Tharp.

Who knows what will be the next big thing for MicroGroove smaller-diameter tubes? Will it be the growing use of heat pumps; variable refrigerant volumes; new synthetic refrigerants and natural refrigerants; the elimination of leaks from supermarkets; the development of energy-efficient cold display cases; the integration of hot-water systems with air-conditioning; "cold energy" storage; or the rise of zero net-energy homes?

Whatever the future brings, it is a good time to be in product development in the ACR industry. The next big thing in ACR might be made from small tubes. And it may come from your laboratory work bench. Will MicroGroove tubes be the key to your success? Join our discussion group on LinkedIn and let us know what you think [9]. **IAM**

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NOTE: ASME-ATI-UIT-10 = The American Society of Mechanical Engineers (ASME), the Associazione Termotecnica Italiana (ATI), the Unione Italiana di Termofluidodinamica (UIT) and International Centre for Heat and Mass Transfer (ICHMT). Conference on Thermal and Environmental Issues in Energy Systems, Sorrento, Italy, May 2010.

NOTE: See "Technical Materials" box on the home page of microgroove.net for links to MicroGroove technical literature or go directly to www.microgroove.net/technical-literature.

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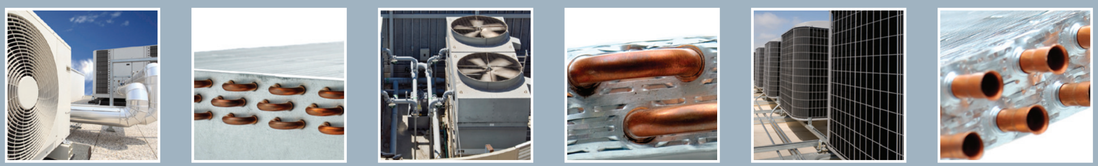

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