Heat Exchangers for Alternative Refrigerants

How small-diameter inner-grooved copper tubes affect refrigerants in exchangers.

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The low toxicity, low reactivity and low flammability of chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) made them extremely attractive as refrigerants for many years. Unfortunately, chlorine is long-lived in the upper atmosphere, where it catalyzes the conversion of ozone to oxygen. CFCs and HCFCs have high ozone-depletion potential (ODP), and these are being rapidly phased out and replaced with alternatives.

Many hydrofluorocarbons (HFCs) also have an extraordinarily high global-warming potential (GWP) and it is desirable to phase out these refrigerants as well. Recognizable by its pink-colored cylinders, R-410A is an HFC that is still widely used in air-conditioning applications even though its GWP is very high.

Natural refrigerants such as propane (R-290) and CO₂ (R-744) offer zero ODP and virtually zero GWP. Other candidates include synthetic refrigerants, such as new hydrofluoroolefins (HFOs), R-32 (an HFC with a moderate GWP) and blends of HFOs with R-32.

Although R-32 is an HFC, its GWP of only 675 is less than one-third of R410A’s GWP of 2,088. Hence, R-32 and blends of R-32 with HFOs are candidates for the replacement of R-410A and other refrigerants. In fact, R-410A is a mixture of R-32 and R-125, chemically known as difluoromethane (CH₂F₂) and pentafluoroethane (CHF₂CF₃), respectively.

Regardless of whether they are natural or synthetic, alternative refrigerants typically place more stringent performance criteria on heat-exchanger designs compared to conventional refrigerants. New designs of heat exchangers may be needed to provide higher capacity for exchanging heat. The exchangers may need to provide high capacity using less refrigerant charge, or they may need to operate at higher pressures or temperatures. It may also be important to prevent corrosion and avoid leakage. Requirements may differ depending on the refrigerant.

Several new technologies are now available for heat exchangers made from copper tubes, allowing for the transition to alternative refrigerants in both room air-conditioning systems and commercial refrigeration systems. The new designs of heat exchangers are uniquely compatible with the new refrigerants. They allow for reduced refrigerant charge, higher operating pressures, improved energy efficiency and resistance to degradation from mold growth. All of these factors contribute to a better life-cycle climate performance (LCCP), an environmental index of growing importance.

Advancements in copper-based heat-exchanger design discussed here include the use of inner-grooved tubes having thin wall and small outer diameters; and the use of higher-strength copper alloy tube for high-pressure refrigerants such as CO₂ (R-744).

Small tubes

Traditional HVAC coil manufacturing technology can be modified to use smaller-diameter copper tubes, resulting in significant improvements in heat transfer. For charge reduction, outer diameters of 7 mm, 6.35 mm and 5 mm are now commonly used and diameters as small as 4 mm are also commercially available. These have wall thicknesses ranging from 0.26 mm to 0.21 mm.

When coupled with enhancements to the copper tubes, such as higher strength, thinner walls and internal micro-grooves, newly optimized heat exchangers can be smaller, more efficient and lower in cost than aluminum microchannel designs, and contain less refrigerant.

Rifling or grooving the inside surface of a copper tube greatly enhances heat transfer for small-diameter copper-tube technology. The inner grooving increases the surface-to-volume ratio, mixes the refrigerant and moves the refrigerant into contact with the interior surface of the tube. The result
is a more efficient combination of conductive and convective heat transfer. The use of smaller-diameter, inner-grooved tubes has contributed to the miniaturization of air-conditioning systems. It has resulted in the development of compact, energy-saving, high-efficiency systems.

Surface enhancements inside the tube increase overall heat-transfer performance. Different inner-groove geometries are available for optimization under various refrigerants and operating conditions (see Figure 1a). Heat exchangers made with tubes with diameters ranging from 7 mm down to 4 mm permit the use of smaller refrigerant charge compared to heat exchangers made with standard 9.53-mm-diameter copper tube. Such heat exchangers are equivalent to those using aluminum microchannel extrusions. The energy efficiency of units using new refrigerants with smaller tubes is similar to that of units using traditional refrigerants with larger diameter tubes. The use of smaller-diameter copper tubes provides a proven, safe solution for air-conditioners using refrigerant R-290, which requires very limited charge size under new regulations for use in air-conditioners.1

As shown in Figure 1b, a herringbone-pattern of grooving on the inside surface of a smaller-diameter copper tube enhances heat transfer compared to a conventional inner-grooved tube without increasing pressure drop. An entire row of condenser tubes can be dropped if this more-efficient tube is used along with an optimized fin design. This performance enhancement means less material is needed in refrigeration applications as well as residential air-conditioning; systems can be made smaller with less refrigerant charge; and raw material costs can be lowered.

When the heat-transfer performance of different types of inner-grooved copper tubes was studied for CO2 heat pumps, the highest heat transfer and the lowest effect of polyalkylene glycol (PAG) lubricating oil was found for the herringbone patterned inner-grooved copper tube.2 The small-diameter tubes have the high strength needed to sustain CO2 operating conditions. Designs have more flexibility compared to microchannel since special circuiting can eliminate maldistribution of refrigerant and oversizing for standard products.3

Performance advantages
Figure 2 further demonstrates the performance advantages of small-diameter, inner-grooved copper tubes. Heat-transfer rate is up 50% compared to the standard inner-grooved tube and it is up at least 100% compared to the standard smooth tube. The observed increased pressure drop with smaller-diameter tubes can be addressed by changes in circuitry design.4

Less usage of tube materials, fin materials and refrigerants contributes to a reduction in overall system costs. In other words, using smaller-diameter copper-tube technology, energy efficiency can be maintained at the system level while reducing the overall size of the system and hence lowering material costs for the system.3 The impact of changing from traditional 9.53-mm (3/8 in.) tubes to 5-mm inner-grooved tubes can be significant:

- A 40%–50% reduction in tube weight;
- A 40%–50% reduction in fin weight;
- At least a 50% reduction in internal volume and thus refrigerant charge;
- A 50% reduction in required wall thickness to meet pressure requirements;
- At least a 20% heat-transfer coefficient that improves heat-exchanger efficiency; and
- A 40% reduction in heat-exchanger cost.

The use of smaller-diameter tubes affects heat-exchanger performance not only on the refrigerant side but also on the air side. Figure 3 shows the compounding benefit of smaller-diameter tubes as shown by the greater effective fin area and higher internal and external heat-transfer coefficient.5

On the refrigerant side, for a given length of tube, a smaller tube size increases the refrigerant pressure drop. Normally, more compressor energy is required to circulate the refrigerant through a given length of tube when the pressure drop is higher. However, in this case, the increase in pressure drop can be offset by using shorter tube lengths and, if necessary,
Alternative refrigerants such as R-32 and CO₂ require higher pressures to condense compared to conventional refrigerants such as R-22. Particularly for CO₂ in refrigeration, tubes and components must exhibit high resistance to pressure. Permissible working pressure is directly proportional to wall thickness and inversely proportional to diameter.

For tubes with the same wall thickness, smaller-diameter tubes can withstand higher pressures than larger-diameter tubes. Moreover, a high-strength copper-iron alloy known as CuFe2P or C19400 can be used to fabricate smooth and inner-grooved seamless tubes with outer diameters of 6.35 mm and above as well as fittings.

High-strength alloys and smaller diameters allow for a reduced wall thickness, which further reduces material usage. Processing can usually be performed with already existing machines and tools since the high-strength alloys are very much brazeable and solderable. These alloy tubes can sustain pressures 100% higher than standard copper tubes for air-conditioning and refrigeration (i.e. up to 12 MPa or 1,740 psi). Corresponding high-strength fittings made from the high-strength alloys are also available.

Since the volume (mass flow) of CO₂ required to achieve the same cooling effect is at least 50% lower than for HFCs, components and tubing can be smaller than conventional installations. In practice, accommodating the high pressures of CO₂ systems is advantageous because the smaller-diameter tubes used to withstand higher pressures also reduce system size and materials requirements. CuFe2P-alloy tubes at small diameters are further advantageous for use in high-pressure CO₂ cascade, transcritical and secondary-loop refrigeration systems since they increase strength without increasing wall thickness.

**R-32 vs. R-410A**

R-32 is an interesting alternative refrigerant because its operating pressures and pressure ratios are similar to R-410A. That is not surprising since R-32 is a component of R-410A. R-32 is a close drop-in replacement that can be used without major system redesign, except for compressor modification, to accommodate the higher discharge temperature.

The latent heat of R-32 is 43%–50% higher than the latent heat of R-410A. As a result, R-32 has a higher volumetric cooling capacity (13% higher) and higher efficiency (2%–3% higher) than R-410A despite a 28% lower mass flow. The higher cooling capacity and efficiency of R-32 facilitates lowering the system charge by at least 15%. Furthermore, the excellent heat transfer, lower vapor density and lower system mass-flow rate of R-32 could lower pressure drops by about 50%. These facts suggest that the performance of R-32 (as well as blends of R-32 with HFOs) can be optimized in compact systems made with smaller-diameter copper tubes. R-32 can facilitate the trend toward lower-charge, compact heat exchangers for addressing the GWP phasedown and reducing A2L flammability risk.

A theoretical comparison was made between R-32 and R-410A systems with equivalent performance. The study showed tube diameters of the heat exchanger and connecting pipe could be reduced 30% when changing from R-410A to R-32 without affecting the performance. That change is equivalent to using small-diameter (5-mm to 7-mm) copper-tube systems. An air-conditioning unit using R-32 could be downsized by up to 15% to 85%–95% of the size of a unit with either R-410A or R-22.

**Software programs for design optimization**

As described earlier, internal surface enhancement and diameter reduction greatly improve the inside-the-tube heat-transfer coefficients. Yet, for the highest possible performance, fin configuration and tube circuits must also be optimized. The interdependencies between the elements of design require a computationally intensive program for optimization.

The small-diameter copper-tube technology platform includes specialized software for heat-exchanger design and system optimization. This software has been developed to enable manufacturers to design high-performance heat exchangers for air-conditioners and refrigeration systems based on small-diameter copper tubes.

Figure 4 shows one such design optimization. In this case, R-290 was the refrigerant in a mini-split room air-conditioner with cooling capacity of 2,600 W. The optimized design of a system made with 5-mm diameter, inner-grooved copper tube demonstrated improved performance compared to a conventional system made with tube diameters of 9.53 mm and 7 mm.

**Similar systems up to 3,000 W of cooling capacity represent 30% of the room air-conditioning market.** The heat exchangers with 5-mm tubes had 50% lower refrigerant charge in the indoor unit and 45% lower charge in the outdoor unit. The total charge was reduced by 36% vs. the original system. The explosion risk of using inflammable natural refrigerants, such as propane, can be decreased by using a smaller refrigerant charge.
Copper fins

One final topic worth mentioning is the use of copper fins to increase LCCP, a topic of great interest in recent years. LCCP is driven mainly by indirect emissions from lifetime operating efficiency.7

LCCP, therefore, is affected by factors that degrade a system’s efficiency over its operating life. One such factor is mold growth. Intrinsic microbial biofilms on air-handling exchanger coils are associated with lowered heat-transfer efficiencies, increased corrosion7 as well as odor issues.10

Pure copper and copper alloys have intrinsic antimicrobial properties. They kill microorganisms on contact and prevent the growth of bacteria and mold. Copper surfaces in the heat-exchanger environment were found to have fungicidal properties and, furthermore, they were found to prevent the germination and release of spores.12 Uncoated copper surfaces limit the growth of pathogenic bacteria by 99.9% and fungi by 99.74% compared to aluminum-based heat exchangers.

Most fungal species totally die off within 24 hours of exposure to copper. Conversely, fungi have been found to survive for a month or more on surfaces made from stainless steel or aluminum.13 The efficacy of copper in killing microorganisms has been proven in rigorous studies that led to the EPA registration of 479 copper alloys as public health antimicrobial touch-surface products.14 Figure 5 shows a long-term performance test of all-copper heat exchangers vs. copper-tube heat exchangers with aluminum fins, in which both units were treated with mold.15

Figure 6 shows how normalized heat flow varies with the amount of mold growth, including mold areas of 0%, 10%, 30% and 60%. Heat exchangers with aluminum fins were compared with all-copper heat exchangers. The heat-transfer performance declined a maximum of 19% with aluminum fins while the all-copper units showed no performance deterioration from mold.

Due to degradation in performance over time, the unit with uncoated aluminum fins consumes more energy, so it has a higher lifetime equivalent CO₂ emissions and LCCP. Indirect emissions account for the largest impact on LCCP. They account for approximately 90% of total emissions for R-410A and up to 99% of the total emissions for a very low-GWP refrigerant like R1234yf.16 Therefore, mitigating as much as a 19% loss of efficiency would have a proportionate effect on LCCP.

Summary and conclusions

Some important conclusions reached in recent years concerning the design of heat-exchanger coils are as follows:

→ New copper-based technologies for heat exchangers are available to enable a smooth transition to alternative refrigerants in residential and commercial heat pumps and air-conditioning systems, as well as commercial refrigeration systems.
Figure 6 Normalized heat flow to mold-growth area.

→ Total heat-transfer performance is improved using small-diameter inner-grooved tubes with additive benefits from both internal surface enhancement and diameter reduction.

→ Alternative refrigerants such as R-290 and R-744 require low charge, compact heat-exchanger designs for which small-diameter copper-tube heat exchangers lower costs and optimize performance.

→ High-strength copper-alloy tube (CuFe2P) in small-diameter tubes that are integrated with advanced compact heat-exchanger design can meet the needs of higher pressure, more compact R-744 refrigeration systems.

→ All-copper heat-exchanger technology with its antimicrobial properties can mitigate the degradation of energy efficiency that is due to mold growth over the operating life of a unit. Avoiding this degradation can improve the LCCP.

References
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