NEW COPPER-BASED HEAT EXCHANGERS FOR R744 REFRIGERANT PART I: NEW TECHNOLOGIES FOR TUBES AND COILS

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ABSTRACT

The replacement of current refrigerants with zero ozone depletion potential (ODP) and virtually zero global warming potential (GWP) refrigerants has important implications for heat exchangers, heat pumps, air conditioners and refrigeration system design, and the materials choices in these designs. The use of CO_2 as a refrigerant requires components to withstand higher pressures compared to conventional refrigerants. Part I presents critical information about smaller-diameter copper tubes and other heat-exchanger technologies, and Part II discusses design principles and presents example case studies for CO_2. Seamless copper tubes with or without inner-grooves can be fabricated from a high-strength copper-iron alloy, reducing wall thickness and thus cost. Coil processing can usually be performed with existing manufacturing equipment since the high strength alloys are brazeable and weldable. Corresponding fittings made from the high strength alloys are also available. Since the volume of CO_2 required to achieve the same cooling effect is much lower than for HFCs, components and tubing can be smaller than in conventional installations. In practice, accommodating the high pressures of CO_2 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 CO_2 cascade, transcritical and secondary-loop refrigeration systems due to their high strength without increasing wall thickness in the transmission lines.

1. INTRODUCTION

This paper presents critical information about how heat exchangers based on round inner-grooved small-diameter copper Microgroove™ tube and newly-developed flat copper microchannel tube can be applied in air conditioning and refrigeration equipment using new alternative refrigerants with special emphasis on R744 as a refrigerant.

Heat exchangers based on MicroGroove™ tubes with 5mm or 4mm outer diameters provide solutions for new refrigerants. These heat exchangers have the high strength needed to sustain R744 (CO_2) operating conditions, and have antimicrobial performance to eliminate mold growth.

The natural refrigerants class includes refrigerants with GWPs of zero or near zero, including ammonia (R717), carbon dioxide (R744), and the hydrocarbons of propane (R290) and isobutene (R600). R717 is already being used extensively in industrial refrigeration systems but is incompatible with copper tubes due to corrosion effects and is rated as a toxic substance.

2. ADVANTAGES OF CARBON DIOXIDE AS A REFRIGERANT

R744 is used in more than two million EcoCute heat pump water heaters (HPWH) in homes in Japan. For cold vending, Coca Cola is mandating that all its beverage coolers be replaced by machines using R744. Increasingly, R744 is being used in industrial and commercial refrigeration in booster transcritical and secondary loop systems as the main refrigerant, and in cascade systems with R404A, R717, and glycol (Emerson, 2010).

The advantages of R744 include (1) an excellent GWP of 1, mitigating the impact of leaks in commercial refrigeration systems; (2) volumetric cooling capacity that is 4.5 to 5 times higher than R410a; (3) a nonflammable A1 designation; and (4) in secondary systems, it requires much lower pump power, typically 5 percent, compared to nonvolatile secondary refrigerants such as water or propylene glycol (Pearson, 2012).

The disadvantages of R744 are its reduced energy-efficiency (COP) compared to R410A (47 percent lower with – 10 °C evaporator and 40°C condenser temperatures) (Leck, 2010) and higher compressor operating pressure (3.5 times higher) (Christensen, 2006), which increases the compressor cost and overall system cost.

Leakage rates in commercial refrigeration systems typically are 30 percent per year versus only two percent over a 20-year operating life for sealed stationary air conditioners. Considering these high leakage rates, R744 is a viable choice in commercial refrigeration. Its use is expanding rapidly in new systems installations, especially in northern latitudes where the effective cooling capacity is highest.

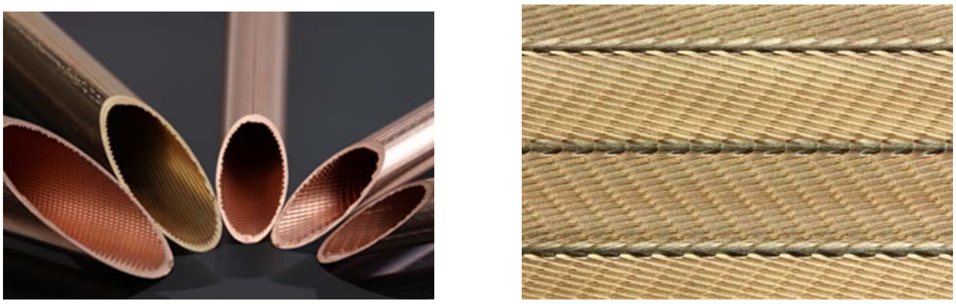


Figure 1. Inner-grooved, small diameter copper tubes (*left*) and enhanced inner-surface (*right*).

3. NEW COPPER TECHNOLOGIES

New copper tube technologies available to meet the operating requirements of the new refrigerants include the following: Small diameter inner grooved thinner wall tubes with outer diameters of 7 mm, 6.25 mm, 5 mm and 4 mm for reduced charge; higher strength copper alloy tube suitable for high pressure refrigerants; extruded microchannel copper tube; multichannel webbed tube from copper strip; very small diameter finless copper tubes; and corrosion resistant alloys and coatings.

3.1. Smaller-diameter, Inner-Grooved Round Tubes

Traditional copper tube/aluminum fin coil manufacturing technology remains prevalent throughout the industry. Significant improvements in heat transfer can be achieved by modifying this existing technology to allow for smaller diameter copper tubes of 7 mm to 4 mm. Additional improvements such as the use of higher-strength alloys, thinner walls and internal surface enhancements result in newer designs of optimized heat exchanger that can be made smaller and more efficient and lower in cost.

A major innovation of small-diameter copper tube technology is that heat transfer is enhanced by rifling or grooving the inside surface of the tube. This increases the surface-to-volume ratio, mixes the refrigerant, and homogenizes refrigerant temperature across the tube, resulting in more efficient convective heat transfer (Ding *et al.*, 2012; Filippini and Merlo, 2011; Yang *et al.*, 2010).

Surface enhancement can significantly increase overall heat transfer performance, with different inner groove geometries available for optimization under various refrigerants and conditions. Smaller diameter, inner grooved copper tubes are referred to as MicroGroove copper tubes. Samples are shown in Figure 1, along with a newer Herringbone Crosshatch™ tube that enhances heat transfer over conventional heat exchanger tubes.

3.2. High-Strength Alloys

For higher-pressure applications and especially for R744 in refrigeration, tubes and components must exhibit high resistance to pressure. Plain and inner-grooved seamless tubes and fittings are available in a high-strength copper-iron alloy known as CuFe2P (and also known as K65, C19400 or CW107C) (Filippini *et al.*, 2014). The alloying elements (and weight percentages) are iron (2.1-2.6), zinc (0.05-0.20), phosphorus (0.015-0.15) and magnesium (max. 0.1). (Figure 2)

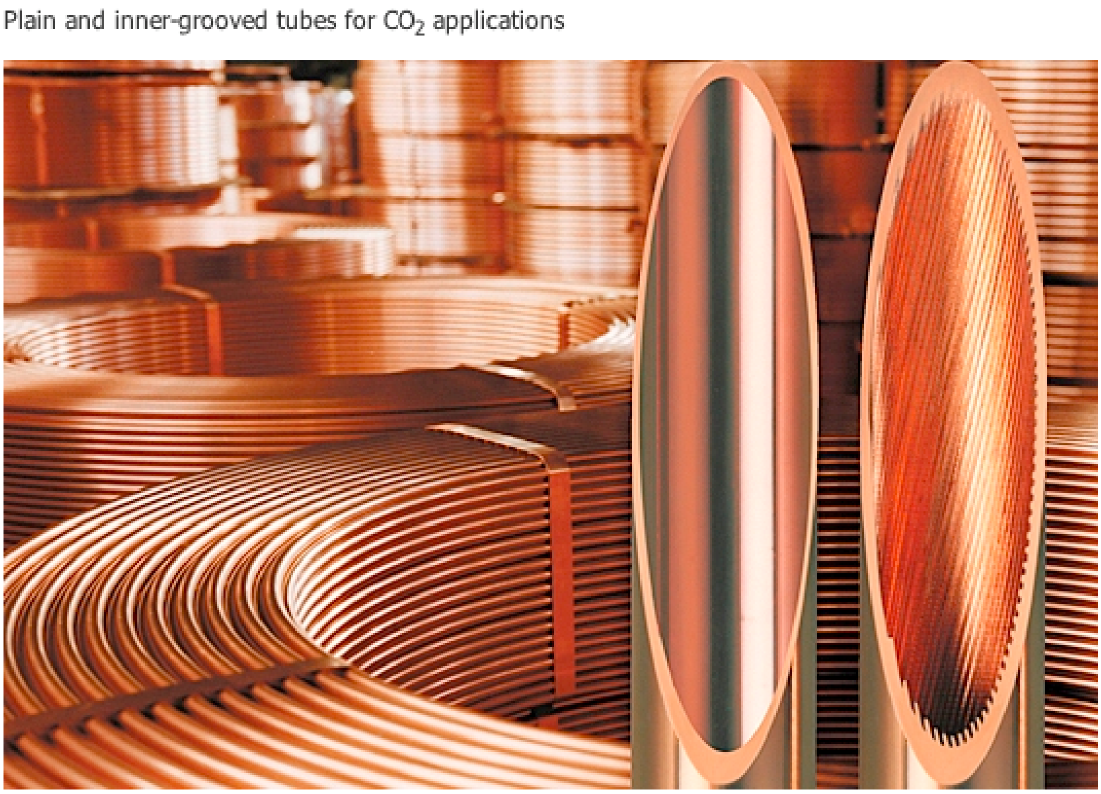


Figure 2. Smooth or inner-grooved tubes made of a high-strength copper alloy (CuFe2P) are suitable for high pressure applications using R744. The CuFe2P alloy consists of copper alloyed with Fe (2.1 to 2.6 wt. %), Zn (0.05 to 0.20 wt. %), P (0.015 to 0.15 wt. %) and Mg (0.10 max. wt. %). Wall diameters range from 0.25 mm to 2.0 mm.

Not only do these alloys allow for a reduction of wall thickness and hence less material usage but also existing machines and tools usually can process these alloys, since they are perfectly brazeable and weldable. These alloy tubes can sustain pressures 100 percent higher than standard ACR tubes.

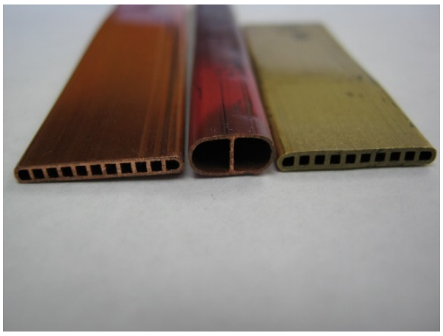
Another type of copper tube (*e.g.*, TECTUBE®_CipsO2) made from deoxidized high phosphorus (DHP) copper is useful up to 14.4 MPa pressure for a 6.35 mm outer diameter with 0.80 mm wall thickness.

3.3. Copper Microchannel Tubes

Copper microchannel tubes extruded with wall thickness of 0.2 mm exhibit a burst pressure of 62 MPa (Kraft, 2014). They are attractive for use at the high temperatures and pressures associated with R744 systems (Kraft and Kochis, 2013; Qi, 2013).

Aluminum extrusions require very thick walls to meet burst pressure requirements at 180 °C (Kraft and Miller, 2007). The thick walls reduce thermal conductivity and increase the size of the heat exchangers. Heat exchangers made of copper microchannel tubes maintain their post-braze strength and burst pressure resistance at 180 °C as well as their high thermal conductivity.

Considering the above, copper microchannel tubes are very competitive on a technical basis. Their ultimate commercial success will depend upon creative heat exchanger designs that minimize manufacturing and materials costs while taking advantage of the unique properties of the microchannel-tube configuration. (Figure 3)



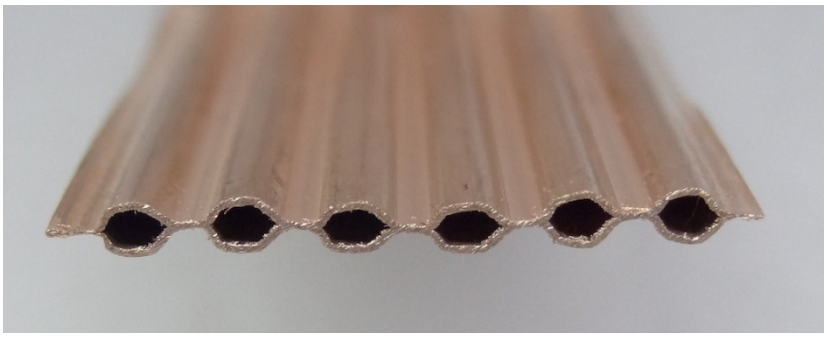


Figure 3. Copper microchannel tubes with eleven channels in copper, two channels in copper and ten channels in a brass alloy (*left*). Webbed tube with six channels is roll-formed from copper strip (*right*).

3.4. Webbed Copper Tubes

Another innovative multichannel technology suitable for R744 applications is the webbed tube. These flat tubes are easily formed from copper strip by squeezing the strips between disc-shaped rollers. The tube burst pressure for a 2 mm channel is 12 Mpa. Additional geometries are being developed, including tubes with channel diameters of 0.8 mm and much higher burst pressures. Figure 3 shows 27 mm wide tube with a channel diameter of 2 mm. The performance of this 2 mm channel tube has been evaluated by simulation to be similar to microchannel tubes.

3.5. Very Small-Diameter Finless Tubes

The lower limits of tube diameters continue to be explored by simulations and measurements on prototypes. At *very* small diameters, finless heat exchanger cores become practical. CFD-based correlations for air-side pressure drop and heat transfer coefficients for bare tube and plain fin-and-tube heat exchangers for tube diameters ranging from 2 mm to 5 mm were recently calculated at the University of Maryland (Bacellar *et al.*, 2014). Experimental validation is underway for these and smaller diameter tubes. Meanwhile, these correlations can be used to select the best geometries for prototyping and laboratory testing.

3.6. Corrosion Resistant Coils and Coatings

Considering that energy efficiency has a large effect on life cycle climate performance (LCCP) (Zhang *et al.*, 2012), it is worthwhile to consider corrosion and biofilm growth as factors in energy efficiency losses.

A corrosion study on heat exchangers was performed by the U.S. Navy for a two year period in a temperate marine environment on the California coast (U.S. Navy Civil Engineering Lab, 1979). The study was performed on all-copper, copper tube/aluminum fin and aluminum tube/aluminum fin units. Units were uncoated or coated with one of three separate coatings: electrostatic polyester, alkyd, and zinc inorganic silicate. Of all the units whether coated or uncoated, all-copper units with the electrostatic polyester coating (0.006 in.) exhibited the superior heat transfer performance after two years.

For locations near the seacoast, a factory-applied tin-plating, sealed coating of the entire tube-and-fin structure is most effective in stopping galvanic corrosion (compared to spray coating in the field after installation). This coating can extend coil life by 3 to 5 times compared to an uncoated coil. A coil with copper tubes and copper fins can benefit from using corrosion resistant tube alloys such as Uniguard™ where there is no risk of galvanic corrosion from dissimilar metals of copper tube/aluminum fin.

3.7. Resistance to Biofilm Growth

Several studies have compared microbial growth on all-copper coils with coils made of copper tubes and aluminum fins and evaluated its effect on energy efficiency and air quality in buildings and public buses. (Ding, 2007; Noyce *et al.*, 2006; Schmidt, 2012; Weaver *et al.*, 2010; Characklis, 1990; Rose *et al.*, 2000; Environmental Protection Agency, 2008)

In a long-term performance test of all-copper heat exchangers versus copper tube / aluminum fin heat exchangers, both units were treated with mold. The all-copper units exhibited no mold growth and showed no performance deterioration from mold, whereas the mold-treated aluminum units exhibited considerable mold growth of up to 60 percent of the frontal area and had a 19 percent reduction in heat flow rate due to mold growth alone (Ding, 2007).

Mold growth occurred on 60 percent of the surface area of the aluminum heat exchanger after 4,800 cycles, which is equivalent to about four years of operation. The capacity loss rate for the aluminum unit was 27 percent, which was 3.7 times greater than the 5.8 percent loss for the all copper units. (Figures 4)

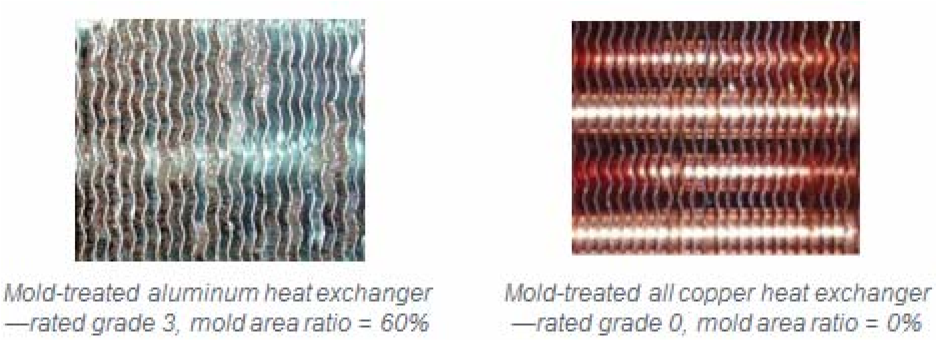


Figure 4. A mold-treated heat exchangers made of copper were unaffected by mold growth while the heat flow rate of a mold-treated aluminum heat exchanger dropped by 19 percent (Ding, 2007).

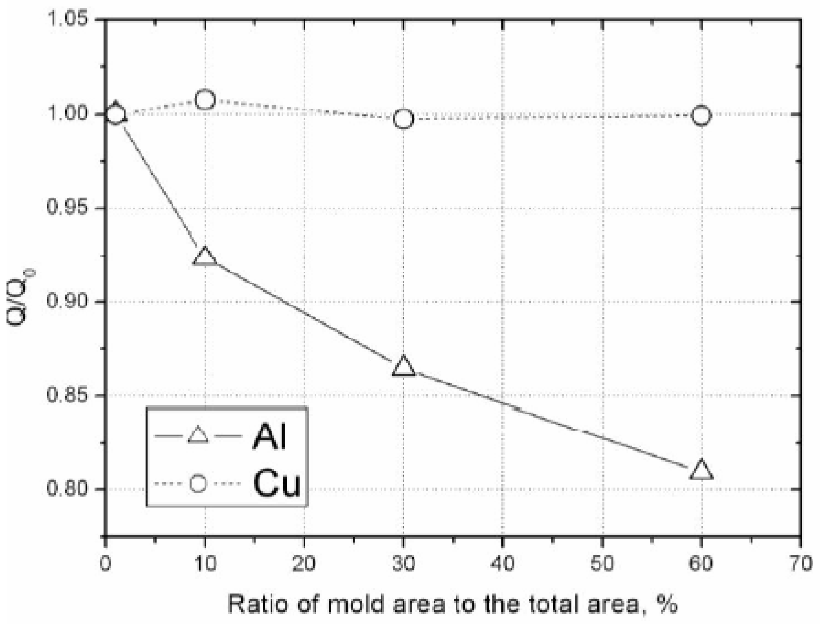


Figure 5. Normalized heat flow to mold growth area on aluminum fins and all-copper heat exchangers with mold areas of 0, 10, 30 and 60 percent. Performance declined 19 percent with aluminum fins while it remained unchanged with copper fins (Ding, 2007).

3.8 MicroGroove Design Software

To obtain the highest performance from air conditioners made with small diameter tubes, it is necessary to apply certain principles to the design of fin-and-tube heat exchangers, including design principles for fin-configuration and tube circuitry. The interdependencies of these design elements necessitate the use of a computationally intensive optimization program; therefore, within the small diameter copper tube technology platform, specific software for heat-exchanger design and system-optimization software has been created to assist manufacturers in the development of high performance heat exchangers based on small diameter copper tube. This software is described in more detail in Part II of this paper.

4. HIGH PERFORMANCE HEAT EXCHANGERS

Greater energy efficiency and smaller overall system size can be achieved at a lower material cost using smaller diameter copper tube technology. The lower material cost is a consequence of the reduced usage of tube and fin materials and refrigerants, each contributing to the overall cost reduction of the system. The overall savings of changing from traditional 9.52 mm (3/8 inch) tube to 5 mm tube for conventional refrigerants has been reported as follows: 40 to 50 percent reduction in tube weight and in fin weight; 15 to 100 percent increase in heat transfer coefficient; and a 40 percent reduction in heat exchanger cost (Holland, 2013).

Higher pressures typically are required to condense newer refrigerants (e.g. R410a, R32 or R744) compared to traditional refrigerants that are being phased out (R22). Working pressure is directly proportional to wall thickness and inversely proportional to diameter. So for tubes with the same wall thickness, smaller diameter tubes can withstand higher pressures than larger diameter tubes.

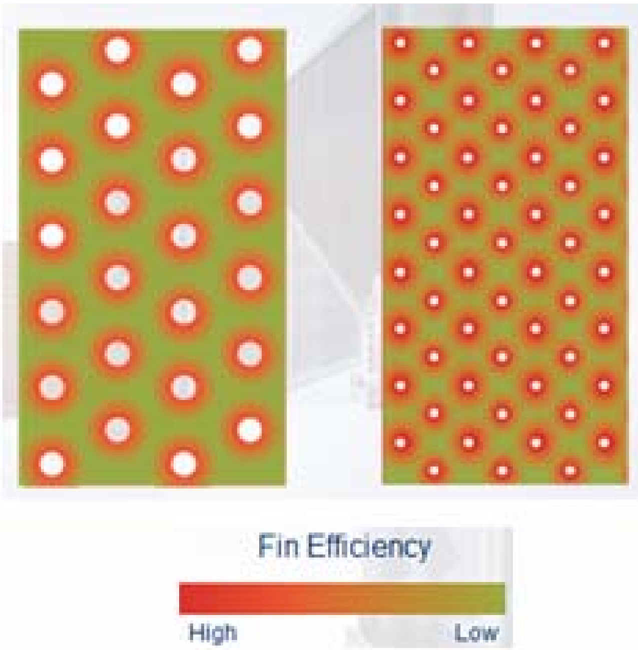


Figure 5. Fin hole patterns for 9.52 mm tube (left) and 5mm tube (right) show more primary heat transfer effective area for the smaller diameter tubes.

The use of smaller-diameter tubes affects heat exchanger performance on both the air side and refrigerant side, allowing for higher heat transfer coefficients inside and outside the tubes.

On the airside, the fin size is determined by balancing the heat transfer resistance between fin and tube. The fin size is typically smaller for smaller-diameter tubes than for larger-diameter tubes. The fin pitch (the distance between fins) is also decreased for smaller-diameter tubes. These factors may decrease the heat transfer capacity and increase airside pressure drop; however, smaller diameter tubes allow for greater effective primary-fin metal area and hence higher heat-transfer coefficients outside the tubes. (Figure 5)

On the refrigerant side, a smaller-diameter increases the refrigerant pressure drop through a tube; consequently, more energy is required to circulate the refrigerant through a given length of tube when the pressure drop is high. However, this pressure drop can be offset by designing heat exchangers with shorter tube lengths and/or increasing the number of tube circuits (Hipchen *et al.*, 2012). A smaller diameter limits the boundary layer near the inner surface and increases of the internal heat transfer coefficient. The smallest amount of heat transfer occurs in the center region of the tube cross section.

The use of round tubes allows for a wide variety of tube circuitry. Options include 1) counter-flow configurations, 2) optimization of mass flux along refrigerant flow direction through tube merging or splitting, and 3) elimination of detrimental tube or fin heat conductions. Circuitry options for aluminum microchannel are considerably more limited in comparison to round tubes (Filippini, 2010).

5. CONCLUSION

Transition to CO_2 in commercial refrigeration in cascade, transcritical R744 booster, and secondary loop systems is already occurring at a quickening pace in Europe and North America and eventually will expand to rest of world. These high-pressure systems will require the use of available smaller-diameter, high-strength alloy, copper tubing, avoiding increased wall thickness and material usage and controlling costs.

Life cycle climate performance is driven largely by indirect emissions from lifetime operating efficiency. Significant degradation in efficiency from mold buildup and corrosion can be addressed by the use of all-copper heat exchangers and the use of new anti-corrosion tin plated coatings on copper tube/aluminum fin heat exchangers.

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