NEW COPPER-BASED HEAT EXCHANGERS FOR R744 REFRIGERANT PART II: SYSTEM DESIGN AND CASE STUDIES

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ABSTRACT

Part I presented critical information on how round inner-grooved small-diameter copper tube and newly developed flat copper microchannel tube can be used with alternative refrigerants and especially 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. Corresponding fittings made from the high strength alloys are also available. Part II examines and presents critical information and case studies relating to system design.
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 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

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. For more information on new copper tube technologies, the reader is referred to Part I.

This second part presents critical information about how heat exchangers based on round inner-grooved small-diameter copper Microgroove™ tube can be applied in air conditioning and refrigeration equipment using new alternative refrigerants with special emphasis on R744 as a refrigerant. Here the focus is on system design, including a discussion of a software platform for applications development and a discussion of safety design principles specific to the development of R744 systems.

2. APPLICATION SPECIFIC SOFTWARE

Application specific software developed by the Copper Alliance specifically facilitates the use of MicroGroove tubes with outer diameters of 7 mm, 6.35 mm, 5 mm, 4 mm and 3 mm in heat exchangers (Wu *et al.*, 2012). It uses computational fluid dynamics and an optimization algorithm in two parts: The first part calculates airside heat-transfer and pressure-drop correlations and optimal fin configuration. The second part searches for the optimal tube circuitry. Experimental verification ensures the accuracy of the simulation predictions.

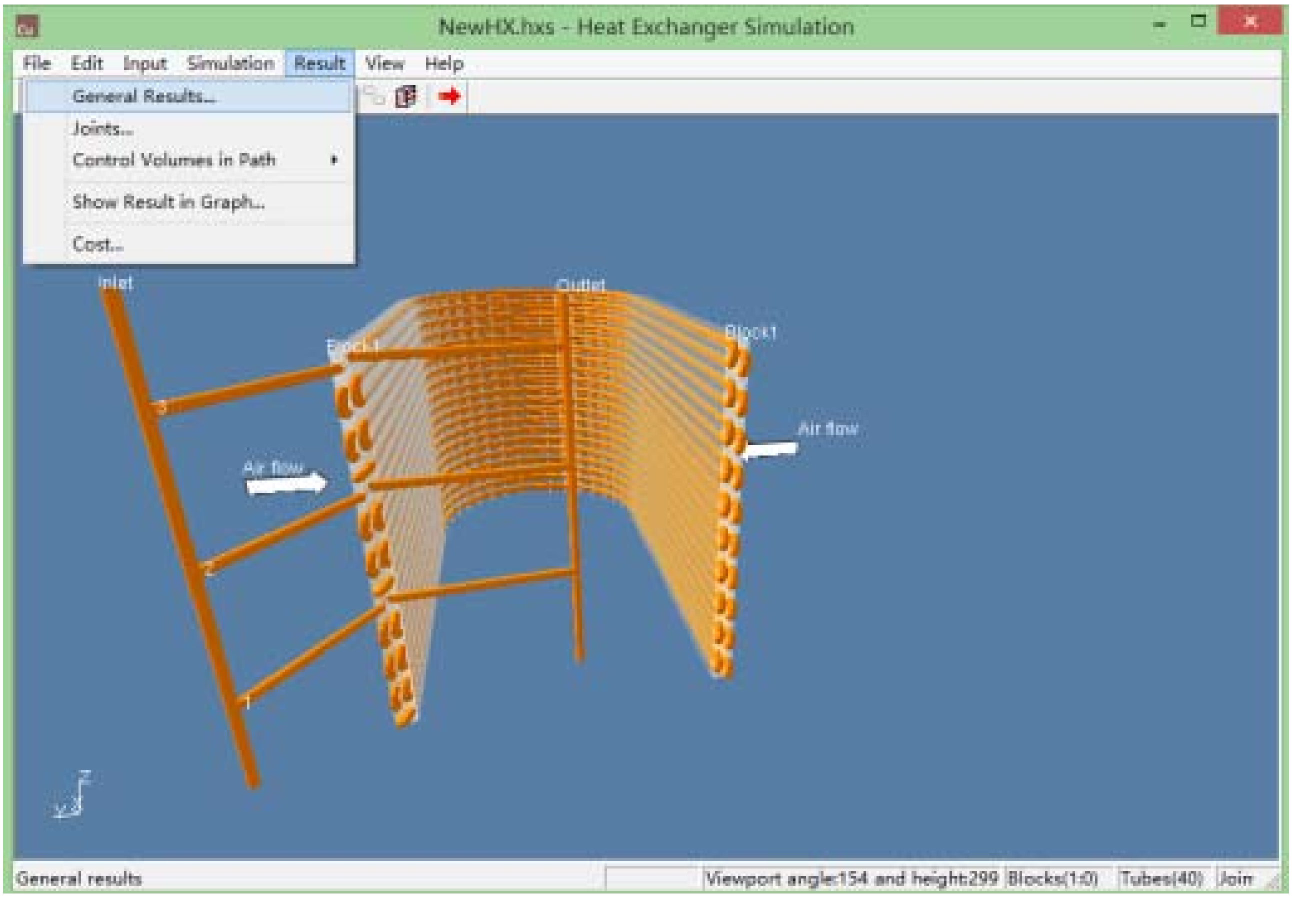

Figure 1. MicroGroove™ heat exchanger simulation software has a graphical user interface capable of two- and three-dimensional views.

The simulations encompass a variety of airflows and refrigerant mass flows. Evaporator and condenser correlation equations have been developed using 3 mm, 4 mm, 5 mm and 7 mm diameter smooth and inner-grooved MicroGroove tubes with plate, wavy, slit and louvered fin designs.

An overall-system simulation package enables optimization of the entire system of compressor, evaporator and condenser together. A cost-analysis module estimates the cost of a newly designed heat exchanger and allows comparison of multiple air conditioners.

The MicroGroove software package has a graphical user interface that makes it easy for users to enter data and observe simulation results in both 2D and 3D views (Figure 1). The software continues to be developed and generalized for new inner-groove geometries, novel fin configurations and alternative refrigerants, including R744.

3. SAFETY AND DESIGN

In light of its nonflammable (A1) classification and its GWP of one, R744 is attractive for use in many specialty applications, including heat pump water heaters, cold vending machines, supermarket refrigeration (cascade systems) and industrial and transport refrigeration systems.

Yet the much higher operating pressures of R744 present safety concerns, adding to the costs of components as well as the overall system cost. Moreover, the EPA SNAP program has cited the concern of the potential lethality of carbon dioxide at high concentrations, which is relevant for passenger cars and rooms with small volumes. In this respect, high pressure is a challenge for aluminum microchannel heat exchangers because of the volume of the headers.

R744 systems are attractive due to their compactness, which explains in part the interest in R744 for automotive air conditioning systems as well as for retail stores. Since the volume to achieve the same cooling effect is much lower for R744 than for HFCs, many components such as compressors and pipes can be made smaller than corresponding components in conventional installations.

The high-pressure R744 systems are advantageous because pipe diameters can be made smaller; in practice, small-diameter circular pipes are very strong under pressure. CuFe2P alloy tube can be applied in these applications without increasing wall thickness. One of the main reasons for adoption of pump-circulated carbon dioxide as a volatile secondary refrigerant for trading floors and for blade-server cooling is the small size of piping.

Laboratory tests were conducted by the LU-VE Group (Uboldo, Italy) on R744 gas coolers and the results were compared with computer simulations (Filippini *et al.* 2014). The 7.94 mm smooth copper tubes were made from a high-strength copper alloy containing a small quantity of iron.

Using 5-mm copper tube for R744 applications can reduce the wall thickness, according to unpublished research performed at Super Radiator Coils, Richmond, Virginia (Yu, 2014). Under pressures of 1100 PSIG (75 bar) for R744 applications, the wall thickness could be reduced to 0.025 inches (1/32 inches or 0.635 mm) of 5 mm tubes compared to 0.049 inch (3/64 inches or 1.245 mm) for a 3/8 inch (9.52 mm) tube. Yu reports that the very low viscosity of R744 in the supercritical condition does not produce a larger pressure drop using 5 mm tube; and that a coil made of 5-mm tubes could be expected to be smaller and less costly compared to a coil made with 3/8 inch tubes.

A study of the heat transfer performance of different inner-grooved copper tubes for R744 heat pumps found the highest heat transfer and the least effect of PAG lubricating oil with herringbone patterned inner grooved copper tube (Kaji *et al.*, 2012). PAG oil is commonly used for lubrication of the compressor and reportedly it has influence on heat transfer performance due to its immiscibility against CO_2 within its working condition.

4. CASCADE REFRIGERATION SYSTEMS

In commercial refrigeration, the high leakage rate of current designs of direct expansion (DX) rack systems is a major concern. Leak rates are typically 8 to 30 percent (Navigant, 2011). The main leakage points in refrigeration systems are at shut-off/Ball/Schrader valves; flare- and mechanical-joints; pressure-relief valves and fusible plugs; condensers; pressure switches; capillary tubes; and return bends on evaporators and condensers. As a solution to such high leak rates, the industry is moving toward several new designs, using R744 either as the sole refrigerant or in combination with ammonia (R717, GWP = 0), HFOs (GWP < 1) or R290 (GWP < 3).

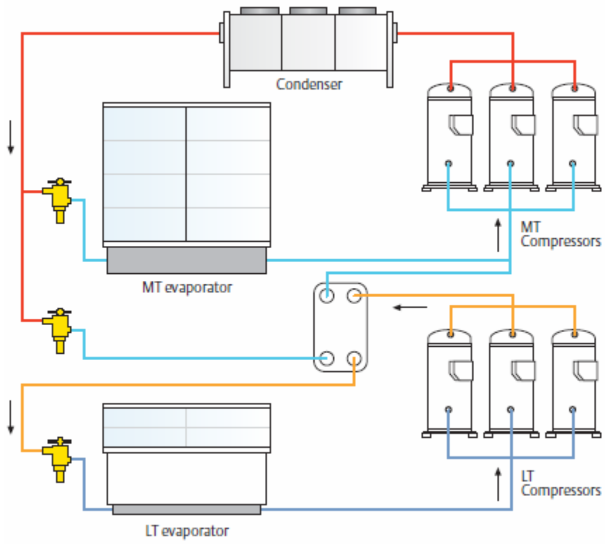

Figure 2. R717/ R744 Cascade refrigeration system for large food freezing and storage warehouses, with R744 in the LT loop (Emerson, 2010)

To reach the lowest temperatures in the cold storage of food, R717/R744 cascade systems are replacing all-ammonia systems. Cascade systems are comprised of two refrigeration systems connected by a common cascade heat exchanger. The latter condenses the low temperature refrigerant (R744) and evaporates the high-temperature refrigerant (R717), as shown in Figure 2.

Different refrigerants (R290, R404a or R717) can be used according to the low and high temperature settings and the system can be optimized for appropriate refrigerants. With R717 as primary refrigerant in a cascade system, only 10 to 20 percent of the charge of a conventional R717 DX system is needed. These cascade systems cost less to operate and the COP is anywhere from 30 to 100 percent higher than for conventional (ammonia-only) systems under full and 50 percent loads (Christensen, 2006).

The low-temperature (LT) circuit has a low condensation temperature so R744 can be applied in subcritical mode without excessive pressures. The discharge pressure (30 to 35 bar) is still within normal design limits for refrigeration pipe work and components (typically 40 bar). These cascade systems are less expensive on the low temperature side with respect to the requirements of compressors; suction piping; valves and insulation; and vessels for liquid separation with insulation. But they are more expensive with respect to the inter-stage cascade heat exchanger; liquid piping valves and insulation; and high-pressure rated components for R744. Overall first installment costs will be 10 to 20 percent lower for cascade systems versus all-R717 systems.

The TerraChill DX2 CO_2 Cascade Rack system from Hussmann is another R744 cascade system for supermarkets. The system is a low-temperature subcritical direct-expansion refrigeration solution using R744. HFC charge can be reduced by 70 percent (with similar leakage reduction) and refrigerant costs reduced by 80 percent compared to typical central direct expansion systems. It also requires correspondingly less copper piping.

Unlike CO_2 secondary or liquid recirculation systems, a subcritical R744 system uses a vapor-compression cycle similar to traditional direct expansion systems. Instead of condensing against ambient air or water, the CO_2 condenses against a primary refrigerant such as R404a. R744 has seven times the volumetric efficiency of R404a, reducing the line sizing tremendously. Smaller volume and higher pressure is well suited for small diameter copper tube.

5. TRANSCRITICAL R744 BOOSTER SYSTEMS

An increasing proportion of supermarkets in Europe and now North America are using R744 as the primary and secondary refrigerant of choice in transcritical R744 booster systems for the high-temperature duties. In these systems, operating temperatures range above and below the critical temperature of CO_2 (which is 31.1 °C). Additional R744 compressors are used to produce refrigeration at low temperatures. The two systems are often kept separate to avoid difficulties with lubricants. In this case, the lower-temperature R744 is condensed by exchanging heat with the evaporator of the high-pressure (higher-temperature) system. The system cools a superheated, supercritical gas into a cooler supercritical gas in a gas cooler with no condensation of the refrigerant.

The pump power required to circulate R744 as a volatile secondary refrigerant is only five percent of the power required to circulate water or glycol in earlier versions of these systems (Pearson, 2012). R744 brings more compact size components including smaller-diameter pipe and tubing, smaller compressors and pumps.

Transcritical R744 booster systems operate most efficiently in cooler climates, which explains why these systems are being installed widely across Scandinavia and Canada, replacing most former systems using HFCs. Scandinavia has also imposed regulations and high taxes to restrict further use of any HFC refrigerants. In North America, Hill Phoenix and Carnot are the leading systems providers leading this trend towards R744 based refrigeration systems.

Installed costs of transcritical R744 booster systems can be 7 to 10 percent higher than traditional HFC DX systems because of the need for an additional heat exhaust and generator. According to the Canadian supermarket chain Sobeys, the system is simpler, costs 50 percent less to maintain, saves 94 percent in refrigerant cost, and uses 15 percent less energy. And it reduces the environmental impact to near zero. Sobeys is in the process of converting its more than 100 stores in Canada to transcritical R744 booster systems.

6. FURTHER APPLICATION EXAMPLES

Another type of R744 system is a secondary loop in which pumps circulate liquid CO_2 through a smaller refrigeration device like a display case at the required case temperature. These can be used for both low and medium temperature applications.

For commercial refrigeration display cases, Second Nature® Low Temp systems developed by Hill Phoenix use R744 as the heat transfer fluid. R744 removes heat efficiently because of its excellent thermodynamic and transport properties. Heat is absorbed in the display case through evaporator coils similar to those used in traditional DX systems. The R744 does not completely evaporate in the coil and is returned to a separator as a mixture of liquid and vapor. The liquid portion of the R744 in the separator is available to be pumped to the display cases and walk-in freezers via copper piping that is significantly smaller than typically required in traditional, direct expansion (DX) systems (Figure 2).

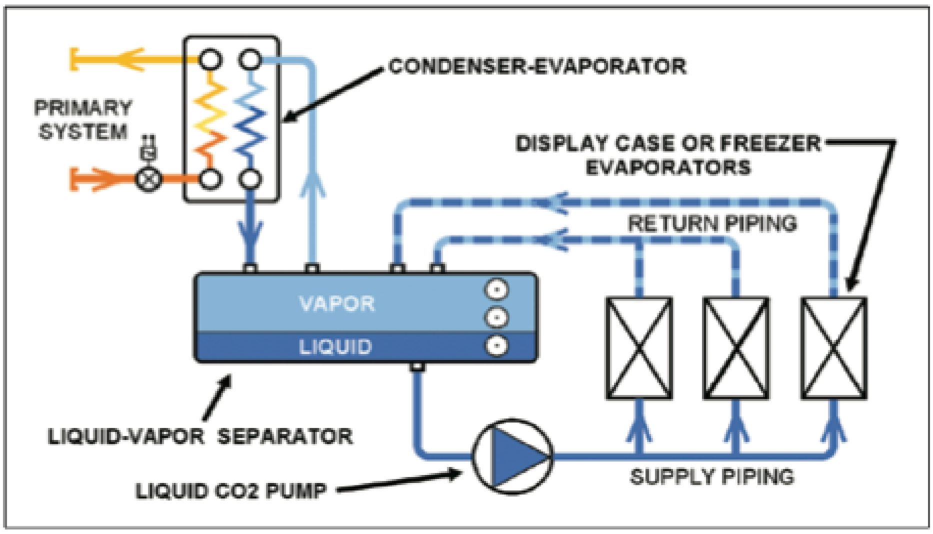

Figure 2. Hill Phoenix Second Nature® Low Temp system using R744. Thin-wall pipes made from CuFe2P high-strength alloy can be used for the supply- and return-piping.

While supermarkets can use brine or carbon dioxide in secondary systems, the cost for pipes and insulation is favorable for R744, considering its low-volume, high flow rate and other transport properties. The estimated costs for pipe and insulation materials for options with R744 are shown in Table 1. Compared to the cost of DX systems, cascade and secondary systems with copper tubing are 83 percent and 42 percent of their cost, respectively, and an additional 67 percent more cost effective than Secondary systems with plastic tubing (Hesse, 1996).

Another example of the design of a refrigeration-application is a hockey rink in Sweden that uses small-bore copper piping in its R744 secondary system along with R-404A in its primary system. Advantage was taken of the very small temperature drop around the carbon dioxide system to allow a larger temperature drop through the concrete to the small copper pipe. The rink has been successful for ice hockey and figure skating.

7. 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.

System	Length (meters)	Diameter (mm)	Insulation (mm)	Relative Costs (percent)
Direct Expansion (Copper Tubing)	100 100	32 10	10 -	100
Secondary Refrigerant System (Plastic Tubing)	- 200	32 10	- 30	167
R744 Secondary Refrigerant System (Copper Tubing)	100 100	18 6	30 10	83
R744 Cascade System (Copper Tubing)	100 100	18 6	10 5	42
Additional Costs (not included): Fittings, insulation				
Additional costs for R744: Extended pressure range, second defrost system				

Table 1. Comparison of estimated costs for pipe material and insulation (Hesse, 1996).

MicroGroove software continues to be developed and generalized for new inner-groove geometries, novel fin configurations and alternative refrigerants, including R744, for which smaller diameter copper tubes are especially advantageous. New alloys, tube designs, coil designs and transmission piping are contributing to a new generation of environmentally friendly refrigeration systems that benefit from the unique properties of R744.

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