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Yoram Shabtay
Heat Transfer Technologies LLC, United States of America, yoram@heattransfertechnologies.com

John Black
Metal Scope LLC, United States of America, jrhblack@gmail.com

Frank Kraft
Ohio University, United States of America, kraftf@ohio.edu

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Yoram SHABTAY[1]*, John BLACK[2], Frank F. KRAFT[3]

[1]Heat Transfer Technologies LLC,
Chicago, Illinois, U.S.A.
(Ph. 630-258-3143, yoram@heattransfertechnologies.com)

[2]Metal Scope LLC,
Chicago, Illinois, U.S.A.
(Ph. 646-683-5615, john.black@copperalliance.org)

[3]Ohio University, Mechanical Engineering Dept.
Athens, Ohio, U.S.A.
(Ph.740-597-1478, kraftf@ohio.edu)

* Corresponding Author

ABSTRACT

The ongoing global effort to replace current refrigerants with zero Ozone Depletion Potential (ODP) and virtually zero Global Warming Potential (GWP) refrigerants has important implications for heat exchangers, air conditioning system design, and the materials choices in these designs. Natural refrigerants with higher flammability, CO_2, HFOs, and HFC – HFO blends each place different requirements on the heat exchanger design, whether it be for higher equipment efficiency, to reduce refrigerant charge, to operate to much higher operating pressures or temperatures, to prevent corrosion or to avoid leakage. This paper presents critical information on how heat exchangers based on round inner-grooved small-diameter copper tube and newly-developed flat copper microchannel tube can be applied in air conditioning equipment using new alternative refrigerants. These technologies have synergies with key refrigerant performance characteristics enabling multiple application opportunities, and they address operating energy efficiency degradation from mold growth on total Life Cycle Climate Performance (LCCP).

1. INTRODUCTION

The ongoing global effort to replace current widely used refrigerants such as R22 and R410A with zero Ozone Depletion Potential (ODP) and virtually zero Global Warming Potential (GWP) alternative refrigerants has important implications for heat exchangers, air conditioning system design, and the materials choices in these designs. Leading refrigerant candidates include the natural refrigerants like propane (R290) with higher flammability, CO_2 (R744), new hydrofluoroolefins (HFO's) and blends of HFOs with R32, a component of R410A, a hydrofluorocarbon (HFC). Each place different requirements on the heat exchanger design, whether it be for higher equipment efficiency, for reduced refrigerant charge, to operate to much higher operating pressures or temperatures, to prevent corrosion or to avoid leakage.

Several copper-based technologies can enable the transition to these new alternative refrigerants in both room air conditioning systems and commercial refrigeration systems, providing synergies with key performance characteristics of the refrigerants, and providing technologies that address the impact of energy efficiency degradation from mold growth:

- Small diameter inner grooved thinner wall tubes with outer diameters of 7mm, 6.25mm, 5mm and 4mm for reduced charge, and wall thicknesses of 0.26 to 0.21mm
- Higher strength copper alloy tube for high pressure refrigerants like CO_2 (R744)
- Copper microchannel tube

2. COPPER TECHNOLOGIES FOR NEW REFRIGERANTS

Traditional copper tube/ aluminum fin coil manufacturing technology when modified for smaller diameter copper tubes of 7mm to 4mm, can achieve significant improvements in heat transfer. When coupled with internal enhancements to the copper tubes such as higher strength, thinner walls and internal micro-grooves, newer optimized heat exchanger designs can be smaller, more efficient, and lower cost compared with aluminum microchannel.

A major innovation of small diameter copper tube technology enhances heat transfer by rifling or grooving the inside surface of the tube. This increases the surface-to-volume ratio, mixes the refrigerant, moves the refrigerant into contact with the interior surface of the tube, and homogenizes refrigerant temperature across the tube, resulting in more efficient conductive and convective heat transfer. The high efficiency of the inner grooved tube stimulates and promotes the development of energy-saving, high efficiency and miniaturization for air conditioning systems. Typically, such surface enhancement can significantly increase overall heat transfer performance, with different inner groove geometries available for optimization under various refrigerants and conditions.

The family of this range of small diameter inner grooved copper tubes, from 7mm down to 4mm O.D., shown in Figure 1, permit significantly smaller refrigerant charge, compared to heat exchangers made with standard 9.53mm diameter copper tube, and equivalent to those using aluminum microchannel extrusions, and they maintain energy efficiency similar to units using traditional refrigerants with larger diameter tube heat exchangers. They have been found to provide a proven and safe solution for air conditioners using refrigerant R290 (propane) which requires very limited charge size under new regulations for use in air conditioners (Ding, 2012).

A newer herringbone inner grooved version of this tube, also in Figure 1, enhances heat transfer over conventional inner-grooved heat exchanger tube without increasing pressure drop. With good fin design, an entire condenser row can be dropped. This performance enhancement has meant lower raw material cost in refrigeration applications, and in residential air conditioning, systems were smaller in size with reduced refrigerant charge and lower raw material cost. A study of heat-transfer performance of different inner-grooved copper tubes for CO_2 heat pumps found the highest heat transfer and the lowest effect of PAG lubricating oil with herringbone patterned inner-grooved copper tube (Kaji, 2012).

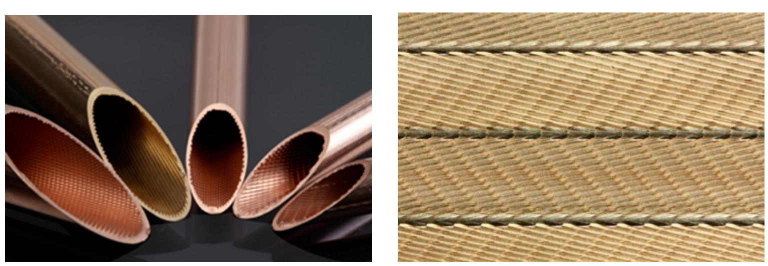


Figure 1. Inner grooved small diameter copper tube and example of enhanced inner tube surface herringbone pattern

The small diameter tubes have the high strength needed to sustain CO_2 operating conditions. They have a higher level of solution flexibility versus microchannel, through special circuiting to eliminate mal-distribution of refrigerant and over-sizing for standard products (Filippini, 2011).

A next generation product nearing commercialization, the copper microchannel extruded tube, produced with a wall thickness of 0.2-0.3mm and channel width of 1.0-1.3mm exhibited a burst pressure of 36 MPa in a post-braze condition (Qi, 2013). Tubes with 0.4mm internal walls and 1mm channels exhibited burst pressures over 62 MPa (Kraft, 2014). This makes these tubes especially attractive for use at high pressures (and temperatures) associated with CO_2 systems. At 180°C and 17 MPa compressor exit conditions, aluminum microchannel extrusions require thicker walls to meet burst pressure requirements. This can result in reduced thermal conductivity and an increase in heat exchanger size. Heat exchangers constructed with copper microchannel extruded tubes will retain more strength in the post-braze condition and burst pressure resistance at 180°C, have high thermal conductivity, and thus maintain a smaller heat exchanger size. In addition, microchannel tube produced with a copper alloy such as brass provides the additional benefits of higher material strength that can lead to even thinner walls and reduced heat exchanger size.

2.1 Performance

The performance effects of using small diameter inner-grooved copper tubes are shown in Figure 2, where enhanced inner-groove shape tube increased heat transfer rate by 50 percent over standard inner-grooved tube, and at least 100 percent over smooth tube. The observed increased pressure drop with smaller diameter tubes can be addressed by changes in circuitry design (Wu, 2012), to be discussed below.

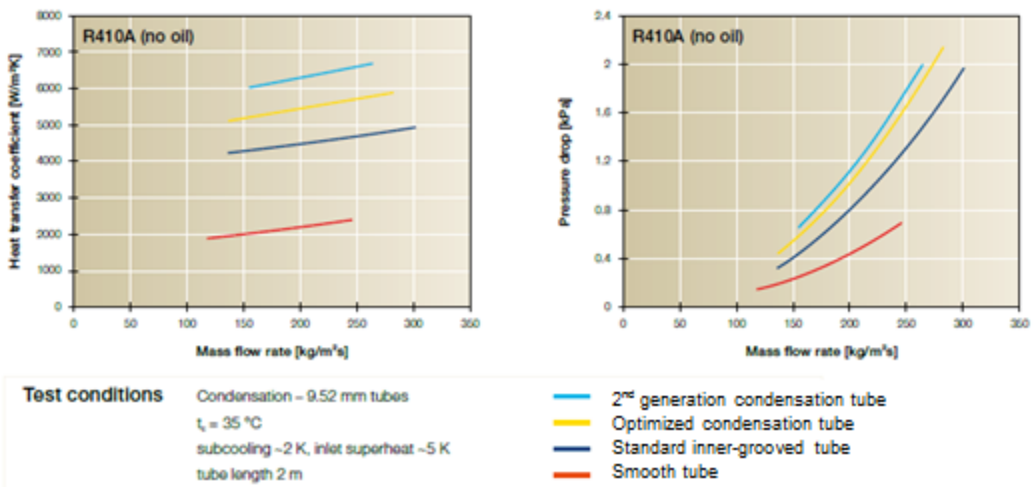


Figure 2. Performance of various inner grooved copper tubes on heat transfer coefficient and pressure drop with R410A refrigerant

Energy efficiency and reduced overall system size can be achieved at a lower material cost with small diameter copper tube technology via reduced usage of tube and fin materials and refrigerants, contributing to overall reduction of system cost (Holland, 2013). The impact of changing from traditional 9.53mm (3/8") tube to 5mm inner-grooved tube can be significant:

- 40 – 50 percent reduction in tube weight
- 40 – 50 percent reduction in fin weight
- 50+ percent reduction in internal volume and thus refrigerant charge
- 50 percent reduction in required wall thickness to meet pressure requirements
- 20+ percent heat transfer coefficient that improves heat exchanger efficiency
- 40 percent reduction in heat exchanger cost

The application of smaller diameter tubes will affect heat exchanger performance on both the air side and refrigerant side. On the air side, the fin size is related to the balance of heat transfer resistance between fin and tube, so fin size for smaller diameter tubes is usually smaller. The fin pitch (the distance between fins), which depends on tube diameter, is also decreased. These may decrease the heat transfer capacity and increase air side pressure drop. But there is also a compounding benefit of smaller diameter tubes as shown by the following equation of heat flow, indicating greater effective primary fin metal area and higher inside and outside heat transfer coefficient, illustrated in Figure 3 (Holland, 2013).

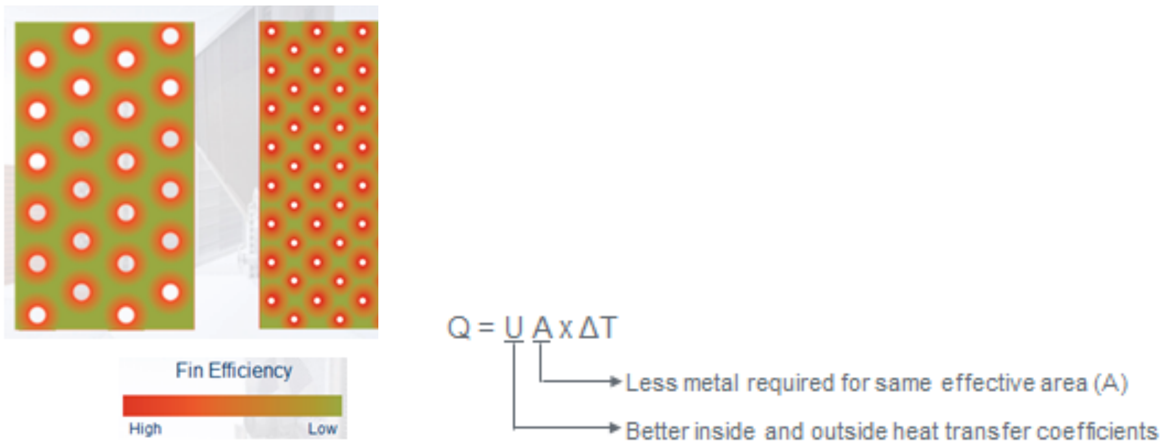


Figure 3. Fin hole patterns for 9.53mm tube (left) and 5mm tube (right) showing more primary (red area around tubes) heat transfer effective area using 5mm tube so fins can be downsized for more compact heat exchanger

On the refrigerant side, smaller tube increases the refrigerant pressure drop. More compressor energy is required to circulate the refrigerant through a given length of tube when the pressure drop is higher. However this increase in pressure drop can be offset by designing heat exchangers with shorter tube lengths and/or increasing the number of parallel tube circuits. It is known that with round tubes, a greater variety of circuitry options are available, than with microchannel, such as counter flow configurations and optimization of mass flux along refrigerant flow direction through tube merging or splitting (Hipchen, 2012). Smaller diameter tube limits the boundary layer near the surface resulting in an advantageous increase of the internal heat transfer coefficient using 5mm inner-grooved tube, as shown in Figure 4, where a 15 – 20 percent increase has been demonstrated versus an inner-grooved 9.53mm copper tube using an HFC refrigerant (Yang, 2010).

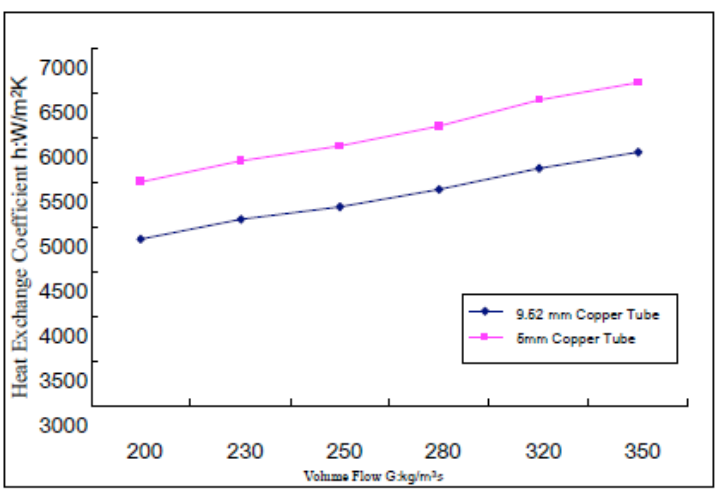


Figure 4. Local heat exchange coefficients for 9.52mm and 5mm inner-grooved copper tubes for different mass flows

Total heat transfer coefficient is improved using small diameter inner-grooved tubes from the additive benefits of both internal surface enhancement and diameter reduction, contributing to a significant total gain in heat transfer performance as shown in the results in Figures 2 and 4.

In order to have a high performance air conditioner with small diameter tubes, it is necessary to develop principles of designing fin-and-tube heat exchangers, including designing the fin configuration and tube circuits. These interdependencies required a computationally intensive optimization program. Therefore within the small diameter copper tube technology platform, specific heat exchanger design and system optimization software has now been developed to enable manufacturers to design high performance heat exchangers for air conditioners and refrigeration systems based on small diameter copper tube.

A result of such optimization work is shown in Figure 5 where R290 refrigerant was used. A mini-split room air conditioner using R290 with cooling capacity of 2,600 watts designed using 5mm diameter inner-grooved copper tube demonstrated improved performance over a conventional system with 9.53mm and 7mm tubes. Systems like this up to 3,000 watts cooling capacity represent 30 percent of the room air-conditioning market. The heat exchangers with 5mm tube had 50 percent lower refrigerant charge in the indoor unit and 45 percent lower charge in the outdoor unit. Total charge was reduced by 36 percent versus the original system (Zheng, 2014)

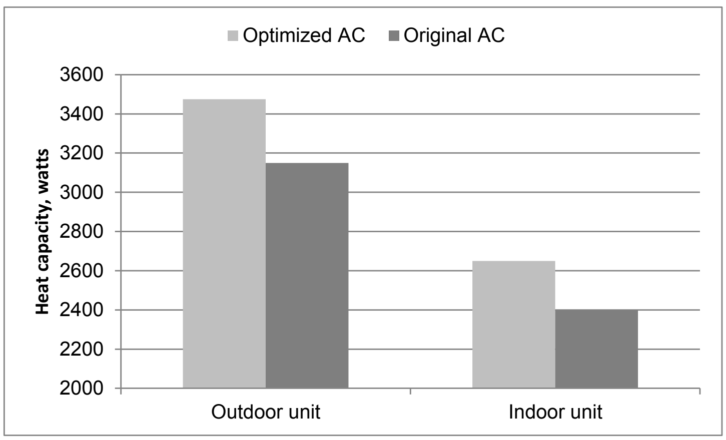


Figure 5. R290 split system comparison of cooling capacity between a conventional unit and optimized unit using 5mm copper tube

Enabled by the smaller refrigerant charge, the explosion risk of using inflammable natural refrigerants like propane can be decreased. Higher pressures typically are required to condense alternative refrigerants like R32 or CO_2, compared to traditional refrigerants that are being phased out (i.e. R22). Permissible 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, and particularly for CO_2 in refrigeration, tubes and components must exhibit high resistance to pressure.

Smooth and inner-grooved seamless tubes and fittings are available in high-strength copper-iron alloy known as CuFe2P or C19400, with outer diameters of 6.35mm and above. Reduced wall thickness is possible, which reduces material usage. Processing can usually be performed with already existing machines and tools as the alloys are very brazeable and solderable. These alloy tubes can sustain pressures 100 percent higher than standard copper tubes for air conditioning and refrigeration, up to 12 MPa (1,740 psi), with corresponding high strength fittings. Since the volume of CO_2 required to achieve the same cooling effect is at least 50 percent lower than for HFCs, components and tubing can be smaller than conventional installations. In practice the high pressure of CO_2 has proved to be an advantage because it results in the need for very small diameter tubes, which are very strong under pressure. CuFe2P alloy tubes at small diameters are advantaged for application in high pressure CO_2 cascade, transcritical, and secondary loop refrigeration systems due to their high strength without increasing wall thickness.

R32 is another interesting alternative refrigerant which has properties of similar pressure and pressure ratio to R410A, being a component of R410A, making it a close drop-in replacement without major system redesign except for compressor modification to accommodate the higher discharge temperature. It has a higher volumetric cooling capacity (+13 percent) and higher efficiency (+2 -3 percent) than R410A, despite a 28 percent lower mass flow, due to a higher latent heat (43 – 50 percent) (Pham, 2012). The higher cooling capacity and efficiency of R32 facilitates at least a 15 percent lower system charge. With its excellent heat transfer, lower vapor density and lower system mass flow rate, about a 50 percent lower pressure drop is expected, suggesting that the properties of R32 (and R32-HFO blends) can be optimized in small diameter copper tube compact systems. This can facilitate the direction toward lower-charge, compact heat exchangers for addressing the GWP phase down and reducing A2L flammability risk.

At an equivalent performance level, a theoretical comparison between using R32 and R410A found a reduction of 30 percent in the diameters of heat exchanger tube and connecting pipe using R32, synergistic with small diameter (5mm to 7mm) copper tube systems. The ultimate volume ratio of an air-conditioning unit using R32 could be downsized to 85 – 95 percent of the size of a unit with either R410A or R22 (Dieryckx, 2012).

2.2 Copper microchannel tube

Copper microchannel tube produced by hot extrusion, shown in Figure 6, is a unique, precision thin-wall multichannel copper profile (Kraft, 2013). High efficiency heat exchangers, as shown, have been produced where the extruded tubes were furnace brazed to serpentine louvered copper fins (Shabtay, 2011). The copper microchannel tube has the following advantages over the aluminum microchannel:

- Greater heat exchange (thermal conductivity)
- Higher strength for high pressure applications
- Better long-term durability and general resistance to corrosion
- Lower cost of maintenance when metal-work is required
- More compact heat exchangers may be possible, due to higher strength and conductivity
- Ability to be in contact with water (in heat pump water heater application)
- Ease of joining (brazing and soldering) and field repair, including transition joints. (Aluminum heat exchangers often require special and/or costly transition connectors to the system)

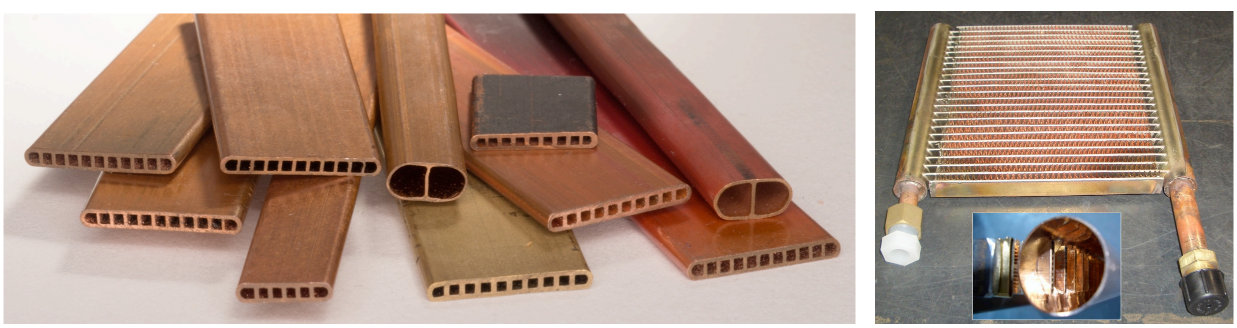


Figure 6. Copper microchannel tubes and heat exchanger

Although not yet commercially available, the copper microchannel tubes show promise and are very competitive with aluminum microchannel on a technical basis for certain applications. The ultimate decision to use this product will rely on creative heat exchanger design that can minimize manufacturing and materials costs while taking advantage of the properties that the copper microchannel tube configuration has to offer, as noted above.

Copper microchannel heat exchangers are suited for these applications:

- High pressure heat exchangers using CO_2 refrigerant
- Compact high performance heat exchangers for military applications

- Gas to water heat exchanger for circulating water refrigerant split systems
- Brazed heat exchangers for demanding environments
- All-copper antimicrobial heat exchangers
- Water heating heat pumps

Operating conditions for components on the high-pressure side of CO_2 refrigeration systems are 17.6 MPa and 180°C. Test and design requirements for the failure pressure at that temperature may be 2 to 3 times greater. For a tube that has a channel-width of 1 mm, and a wall-thickness of 0.30 mm, the following results are predicted, in the post-braze condition (Cuprobraze for copper and Nokolok brazing for aluminum). These values were determined by the methodology presented in (Qi, 2013) and (Kraft, 2007):

UNS C12200 copper: 47.6 MPa
AA 3102 aluminum: 18.6 MPa
AA 3003 aluminum: 26.9 MPa

The maximum pressure ($p_{\max}$) was determined with the following equation (1), where w_0 is the initial channel width and t_0 is the initial internal wall thickness.

$$p_{\max} = \frac{2}{\sqrt{3}}\bar{\sigma}\left[\frac{w_0}{t_0}\exp\left(\sqrt{3}\bar{\varepsilon}^*\right)+1\right]^{-1} \tag{1}$$

The true stress, $\bar{\sigma}$, is a function of true strain, $\bar{\varepsilon}$, and failure takes place at the instability strain, $\bar{\varepsilon}^*$. The instability strain is determined by solving equation (2),

$$d\bar{\sigma}/d\,\bar{\varepsilon} = \sqrt{3}\bar{\sigma} \text{ for } \bar{\varepsilon} \tag{2}$$

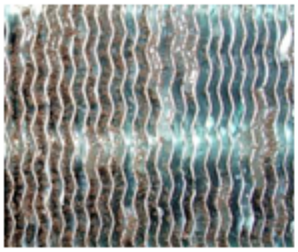
For C12200 copper in the post-braze condition, the true stress equation (3) was determined by (Qi, 2013) as follows:

$$\bar{\sigma} = 340 - 306\exp\left(-5.2\bar{\varepsilon}\right) MPa \tag{3}$$

2.3 Effects of copper finned heat exchangers on LCCP

Life cycle climate performance (LCCP) has been shown to be driven mainly by the indirect emissions effect from lifetime operating efficiency (Pham, 2012). LCCP will therefore be significantly affected by key contributing factors leading to degradation of efficiency over the operating life, which includes mold growth. Intrinsic microbial biofilms on air handling exchanger coils are associated with lowered heat transfer efficiencies and increased corrosion (Characklis,1990) as well as potential odor issues (Rose, 2000). Pure copper and copper alloys have intrinsic antimicrobial properties that 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 prevented the germination and release of spores (Schmidt, 2012). Uncoated copper surfaces have shown they limit the growth of pathogenic bacteria by 99.9 percent and fungi by 99.74% of that observed on the control, aluminum-based heat exchangers. Most fungal species show a total die off within 24 hours of exposure to copper, but conversely, fungi have been found to survive for a month or more on surfaces made from stainless steel or aluminum (Weaver, 2010).

This effectiveness of copper has been proven in rigorous studies that led to EPA registration of 479 copper alloys as public health antimicrobial touch-surface products (EPA, 2008). In a long-term performance test of all copper heat exchangers versus copper tube/aluminum fin heat exchangers shown in Figure 7, both units were treated with mold (Ding, 2007).



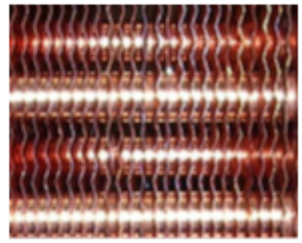


Figure 7. Mold treated aluminum and all copper heat exchangers after 28 days incubation, showing no growth on the all copper unit

After 28 days of incubation, the all copper units exhibited no mold growth, whereas the mold-treated aluminum units exhibited considerable mold growth of up to 60 percent of the frontal area. Figure 8 shows test results of normalized heat flow to mold growth area on aluminum fins and all-copper heat exchangers with mold areas 0%, 10%, 30% and 60%, showing heat transfer performance declined a maximum of 19% with aluminum fins while the all-copper units showed no performance deterioration from mold. Due to lower efficiency, the unit with aluminum fins will consume more energy, resulting in higher lifetime equivalent CO_2 emissions and LCCP. Since indirect emissions account for the largest impact on LCCP, approximately 90% of total emissions for R410A and up to 99% for a very low GWP refrigerant like R1234yf (Zhang, 2012), mitigating as much as a 19 percent loss of efficiency would have a similarly proportionate impact on LCCP.

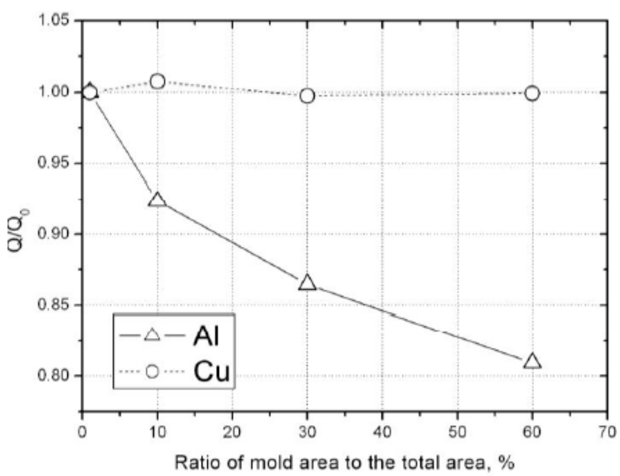


Figure 8. Normalized heat flow to mold growth area

3. CONCLUSIONS

- New copper-based technologies for heat exchangers are available to enable a smooth transition to alternative refrigerants in residential and commercial air-conditioning systems and commercial-refrigeration systems, which provide synergies with key performance characteristics of the refrigerants.
- 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 R290 (propane) and R744 (CO_2), and to a lesser extent R32 and R32-HFO blends, require low charge, compact heat exchanger designs for which small-diameter copper-tube heat exchangers provide synergies, lower cost, and further performance optimization.
- High-strength copper-alloy tube (CuFe2P) in small diameters or in copper microchannel integrated with advanced compact heat-exchanger design meet the needs of higher pressure, more compact R744 (CO_2) refrigeration systems.
- Next generation product, the copper microchannel extruded tube, with thin wall thickness and high burst pressure resistance, is especially attractive for use at high pressures (and temperatures) associated with CO_2 systems.
- All-copper heat exchanger technology with its antimicrobial properties can mitigate the impact of energy-efficiency degradation due to mold growth over a unit's operating life, which has the largest positive leverage on Life Cycle Climate Performance.

NOMENCLATURE

A	heat transfer surface area	(m^2)
GWP	Global Warming Potential	
HFC	Hydrofluorocarbon	
HFO	Hydrofluoroolefin	
LCCP	Life Cycle Climate Performance	(kg CO_2-Equivalent)
ODP	Ozone Depletion Potential	
p_{max}	maximum pressure	(MPa)
Q	heat transfer	(W)
Q/Qo	true stress	normalized heat flow
$\overline{\sigma}$	true stress	(MPa)
$\bar{\varepsilon}$	true strain	(% elongation)
$\bar{\varepsilon}^*$	instability strain	(% elongation)
SEER	Seasonal Energy Efficiency Ratio	(Btu/Wh)
U	overall heat transfer coefficient,	(W/ m^2K)
ΔT	inlet and outlet temperature difference	(K)
w_0	initial channel width	(mm)
t_0	initial internal wall thickness	(mm)

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