

The Development of Heat Exchangers for Energy-Efficient, Low-GWP Refrigerant Appliances

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Manufacturers are highly motivated to develop heat exchangers that satisfy three often contradictory criteria: low refrigerant-charge, high energy-efficiency and low cost. Smaller diameter copper tube heat exchangers help manufacturers reach all three of these objectives.

For many appliance applications, coil designs have been optimized for traditional tubes. Today, the traditional tube diameter is no longer the benchmark for coil design (Figures 1 and 2). The term “traditional” in this context typically refers to copper tubes with an outer diameter of 9.52 mm (3/8 inch), a size widely used in past decades.

For room air conditioners, the industry migrated to 5-mm diameter tubes several years ago. Nowadays, if you purchase a window-type air-conditioner from a big box retail chain, it will likely have 5-mm copper tubes in both the evaporator and the condenser coils. These units are produced in high volume and millions are already in use globally.

In this paper, important advances with respect to the use of smaller diameter copper tubes in heat exchangers for appliances are summarized.

Airside Heat Transfer

Airside heat transfer around smaller diameter tubes can be modeled with unprecedented accuracy, opening



Figure 1. The heat exchanger coils made from 5 mm copper tubes are used in a wide variety of appliances. Source: Spirotech

the door to new, more energy efficient heat exchanger designs.

Airflow around smaller diameter tubes faces less resistance than airflow around traditional tubes (Figure 3). Research supported by the International Copper Association (ICA) and conducted by Optimized Thermal Systems, Inc. (OTS) compares the performance of slit fins and louvre fins for smaller diameter (3 mm to 5 mm) copper tubes [1, 2].

Previously only the largest OEMs could afford to perform such coil optimization through CFD modeling. Designers were guided by general principles, or “rules of thumb,” and fin designs had not been optimized for smaller diameter tubes. As described in a previous issue of *International Appliance Manufacturing*, a research consortium in China used a knowledge-based evolution method (KBEM) to eliminate unfeasible or impractical designs before the simulations are performed, allowing for a more efficient sampling of the design space [3].

Now, thanks to the Center for Environmental Energy Engineering (CEEE) at the University of Maryland and OTS, techniques for optimizing coil designs are available to users of CoilDesigner®, a highly customizable software tool that allows designers to simulate and optimize the performance of heat exchangers [4]. OTS works with coil designers around the globe to optimize heat

exchanger geometry, including the use of smaller diameter tubes. CoilDesigner includes the latest heat transfer and pressure drop models published in the open literature and users also can plug-in proprietary models. OEM users can shorten product development costs and quickly bring products to market.

Refrigerant-Side (Inside Tube) Heat Transfer

Simulation software uses correlations developed for both airside and refrigerant side heat transfer, building on the research results from many laboratories around the globe. Thus, the prediction accuracy of such simulations depends on the availability and accuracy of these correlations.

Seminal research was performed at the Institute of Refrigeration and Cryogenics of Shanghai Jiao Tong University [5]. Now laboratory research results are also available for new low-GWP refrigerants in smaller diameter copper tubes. In particular, laboratory experiments on MicroGroove tubes were conducted at the University of Padova, Padova,

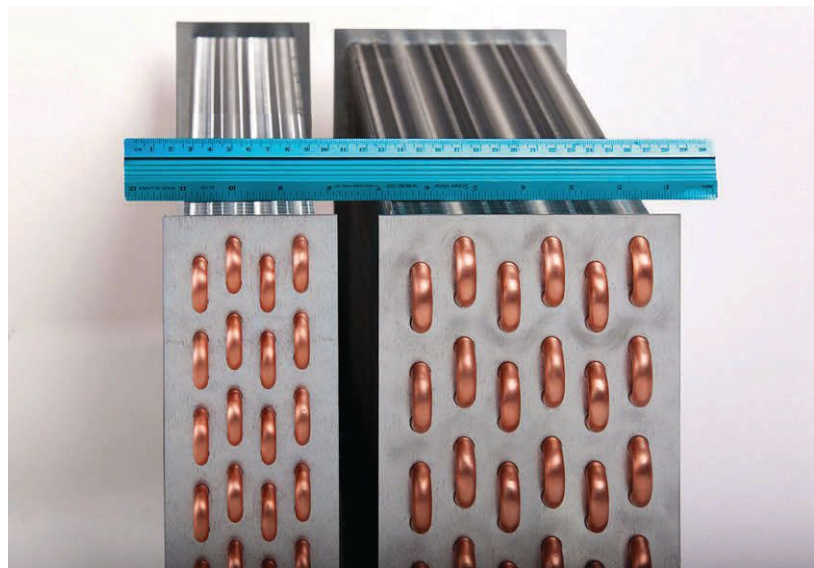


Figure 2. The new benchmark for the outer diameters of tubes for high efficiency heat exchanger coils is 5 mm (left) or 7 mm (right).

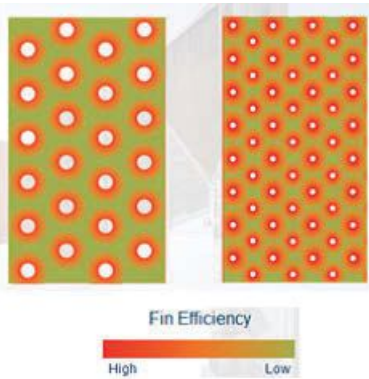


Figure 3. Airflow around smaller diameter tubes faces less resistance than airflow around traditional tubes.

Italy [6,7]; Tokyo University of Marine Science and Technology [8]; and Kyushu University, Fukuoka, Japan [9].

Such research provides predictive correlations that can be used to simulate the performance of coil designs that use smaller diameter copper tubes with a variety of inside-the-tube enhancements (i.e., microfins) for low- and ultra-low GWP refrigerants (Figure 4).

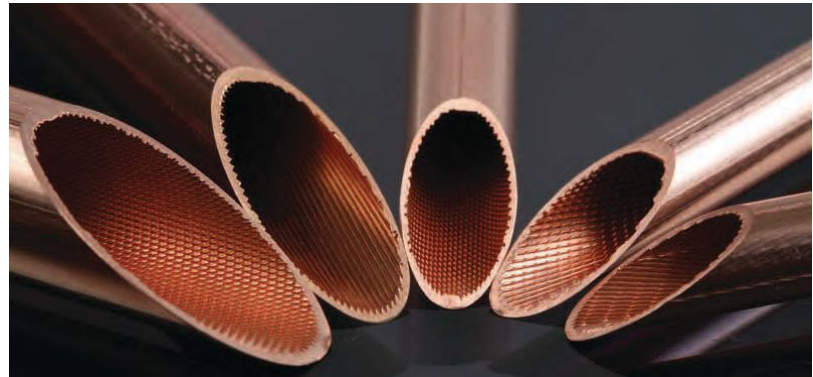


Figure 4. Often called “microfins” in the technical literature, inside-the-tube surface enhancements increase the heat transfer coefficients and decrease the pressure drop for refrigerants flowing through MicroGroove copper tubes. Microfin performance as it relates to low-GWP refrigerants is an ongoing area of research.

According to the Padova group, “the literature about smaller diameter microfin tubes (i.e., inner diameter lower than 6 mm or so) is poor if compared with larger tubes.” They aptly dubbed these “mini microfin-tubes” in contrast to traditional (larger diameter) microfin tubes. These researchers measured flow boiling heat transfer and pressure drops inside copper tubes with internal enhancements [6]. In this first paper, the copper tubes had an outer diameter (OD) of 5 mm

and the refrigerant was R134a. The saturation temperature was 10 °C. The vapor quality was varied from 0.1 to 0.95; the mass velocity from 100 to 800 kg/m²s; and heat flux from 15 to 90 kW/m². As expected, the dominant mechanisms are convective boiling at low heat fluxes, and two-phase forced convection at high heat fluxes. The authors concluded that the results highlight the promising heat transfer capabilities of mini microfin tubes during flow boiling. Looking forward, they state that “additional heat transfer measurements with different tube diameters, different helical geometries, and different type of refrigerants are surely needed.”

In a second paper, the Padova group also measured flow boiling heat transfer and pressure drop for an ultralow-GWP HFO1234ze(E) refrigerant inside smooth tubes having an OD of 4 mm [7]. The heat transfer coefficients for the HFO was similar that of HFC134a at the same operating conditions but the pressure drops were 10 to 25 percent higher for the HFO. According to these authors, the heat transfer measurements confirm that HFO1234ze(E) is a very promising

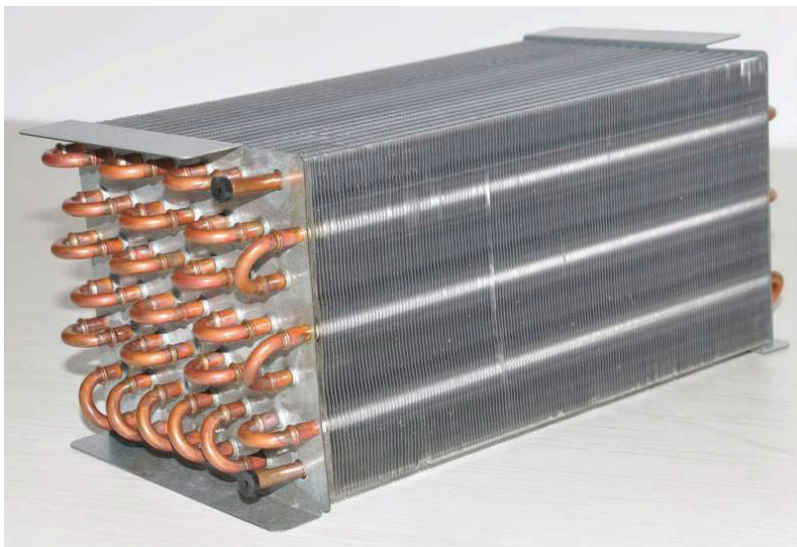


Figure 5. This condenser coil using 5-mm copper tubes is used in an energy saving clothes dryer heat pump. Source: Spirotech

low-GWP candidate for HFC134a replacement.

The Tokyo researchers measured pressure drops and evaporative heat transfer coefficients for R32 refrigerant passing through 4 mm OD copper tubes with a broad range of internal enhancements, including “microfin” heights of 0.1 mm and 0.2 mm [8]. Measurements were made at saturation of 15 °C with mass velocity ranging from 50 to 400 kg/m²s and heat flux from 5 to 20 kW/m².

Meanwhile, the Kyushu group measured heat transfer coefficients for mixtures of R32 with HFOs [9]. This research is especially important because it provides performance data for different compositions of the refrigerant mixtures. “Temperature glide” is known to compromise performance in R32/HFO mixtures compared to single components (i.e., R32 or HFO alone). The Kyushu results provide predictive correlations including the effects of microfins for these refrigerant blends, which are likely to play an important role in future air conditioning and refrigeration systems. The microfins in the 4-mm diameter copper tubes had heights of 0.26 mm.

The Future of Refrigerants

There is little doubt that the use of hydrofluorocarbons (HFCs) will be phased down. It is only a matter of how soon. In October 2016, Kigali, Rwanda will host the next Meeting of the Parties of the Montreal Protocol. An amendment to the Montreal Protocol aims to phase-down the use of HFCs, which are powerful greenhouse gases.

R32 is an HFC similar to methane except that two of the four hydrogen



Figure 6. This heat exchanger coil made with 5-mm copper tubes is designed for cooling R744, an ultralow GWP-refrigerant. Source: Spirotech

atoms have been replaced by fluorine atoms. It has a GWP of 675, which is still quite high but relatively low compared to other HFCs still in use. Hydrofluoroolefins (HFOs) are also compounds of hydrogen, fluorine and carbon but are distinguished from HFCs by being derivatives of alkenes (olefins) rather than alkanes. Researchers are already seeking to understand how R32 and HFOs and blends of these refrigerants behave when they are passed through smaller diameter copper tubes.

Here is where the refrigerant cost versus low GWP comes to a climax. The HFOs have ultralow GWP and factually are less flammable than R32; however, they are currently more costly because production of these compounds has not been scaled up. Meanwhile, R32 is cheaper and more widely available but it is more flammable and has a much higher GWP.

Low refrigerant volumes are universally desirable because of the flammability of low GWP refrigerants.

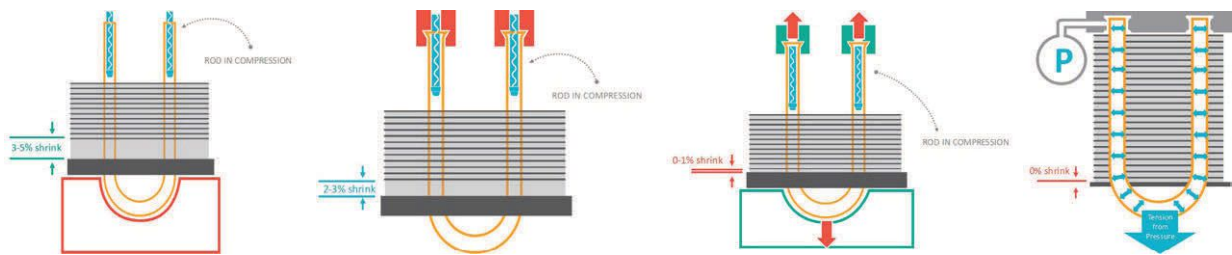


Figure 7. Various methods for expanding copper tubes: (a) mechanical bullet expansion, (b) tension expansion, (c) limited shrink tension expansion, and (d) tubular hydro-expansion.

One of the advantages of smaller diameter copper tubes is that they allow for a reduction in refrigerant volume while still allowing for high efficiencies (Figure 5 and 6).

Applications that use R290 as a refrigerant typically also use smaller diameter copper tubes to reduce the requirements for refrigerant charge. HFOs are not as flammable as R290 but still they are flammable and minimizing refrigerant charge is desirable.

A recent article from the Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University, Shanghai, China reviews research on R290 condensation and evaporation [10]. According to the authors, this review paper is a starting point for future R290 studies and R290 applications in air conditioning systems.

MicroGroove technology can help meet the regulatory requirements for R-290 because refrigerant volumes can be greatly reduced by using smaller-diameter copper tubes. Already, in the US, cold display cases and freezers are meeting safety requirements in light commercial applications; furthermore, propane is gaining acceptance for use in room air-

conditioning systems in India, for example.

In an R290 air-conditioner condenser application from Super Radiator Coils, MicroGroove allowed for a reduction in refrigerant charge and maintained high burst pressures with thinner walls [11]. Copper usage was reduced up to 26 percent while increasing capacity up to 6.5 percent as tube diameters were decreased from 9.52 mm (3/8 in.) and 7.94 mm (5/16 in.) to 5 mm; and tube walls were thinned from 0.41 mm (16 mils) and 0.33 mm (13 mils) to 0.25 mm (10 mils), respectively.

In another application from Super Radiator Coils, smaller-diameter (5 mm) copper tubes were used rather than conventional-diameter (9.52 mm) copper tubes in a heat exchanger design for an R290 refrigeration system. According to Dr. Jian Yu, Director of Product Development at Super Radiator Coils, Richmond, Virginia, tube weight was reduced by 30 percent, fin weight by 47 percent and internal volume for refrigerant by 50 percent, [The smaller diameter tubes had an outer diameter of 0.197 inches, or 5 mm and wall thickness of 0.010 inch; the conventional-diameter tubes had an OD of 3/8 inch, or

0.375 inches, or 9.52 mm; and wall thickness of 0.015 inch.]

Easy Drainage and Cleaning

An advantage of round tube plate fin (RTPF) coils is ease of cleaning and good condensate drainage. The plate fins in RTPF coils are typically vertically oriented and water drains easily from the top to the bottom of the sheets. The tubes penetrate the sheets at right angles and water can easily flow around them. The same holds true for RTPF coils made from smaller diameter copper tubes. There may be more tubes penetrating the plate fins but water flows easily around the smaller diameter tubes.

The open structure of a round tube plate fin (RTPF) is a major advantage of MicroGroove heat exchangers compared to aluminum microchannel heat exchangers, which is why MicroGroove heat exchangers are commonly used in the outdoor evaporators of heat pumps especially in colder climates where frosting may be an issue.

A wavy fin is a plate fin with no holes and so drains better. Wavy fin designs are found to be more effective for heat pumps where the outdoor evaporators may

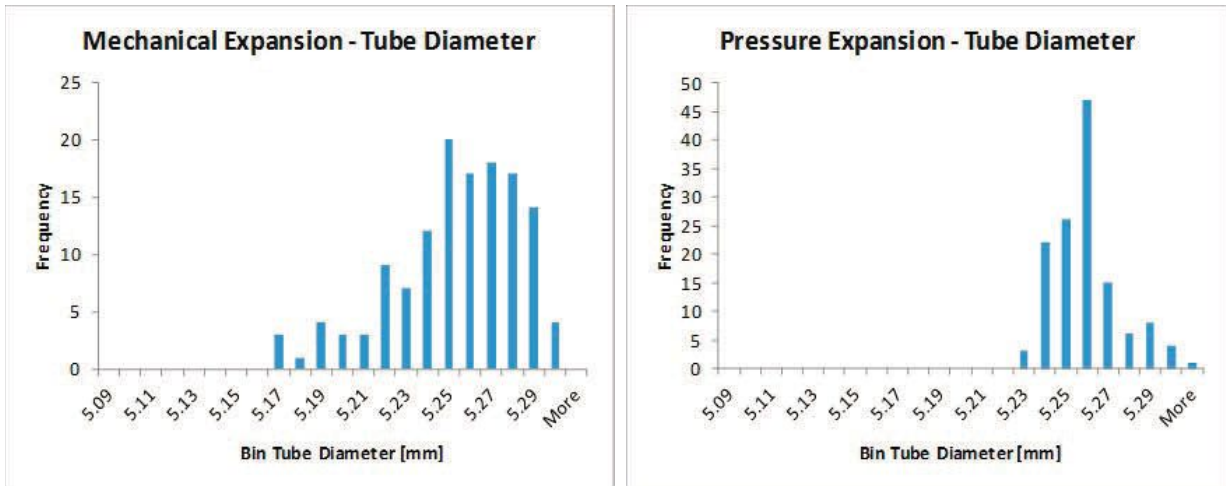


Figure 8. Measurements of tube diameters comparing (a) mechanical expansion with (b) noninvasive pressure expansion.

be subject to frosting and for refrigeration equipment where frosting and condensation cancels the advantages of slit and louvre type fins due to the clogging of the openings.

Also, enhanced fins such as slit or louvered fins aggravate the dust accumulation in the condensers of refrigerated display cabinets [12]. Condensers in display cabinets are especially prone to dust accumulation because they are positioned close to the floor.

Supported in part by International Copper Association, researchers at the Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University, conducted research to examine the feasibility of replacing 9.52 mm copper tubes with 5 mm diameter tubes in the condensers of refrigerated display cabinets [13]. Wavy fins were chosen for this application because of considerations about dust accumulation.

The fin structure was selected by theoretical analysis and the flow

path of 5 mm diameter tube heat exchanger was analyzed using a heat exchanger simulation tool to find a suitable balance between heat transfer and pressure drop. The simulation results suggested that cost of the condenser could be reduced by 26 percent using the 5 mm tube with performance the same as the 9.52 mm prototype. The experimental data validated the simulation results, proving the feasibility of applying the small diameter tubes in display cabinets.

In related research, the CEEE investigated the design space for wavy fin heat exchangers having copper tube outer diameters ranging from 2 mm to 5 mm. They found that existing correlations were not applicable to the design space, thus justifying the need for new equations [14, 15].

Pressure Expansion

The manufacture of RTPF coils from copper tubes and aluminum plate fins requires that the copper tubes be expanded from the inside until they make contact with the collared aluminum fins. Typically the copper

tubes are deformed beyond the yield stress (that is, they are subject to plastic deformation) whereas the aluminum fins are elastically strained. This provides a tight interference fit that conducts heat well between the two metals.

In October 2015 IAM published a preview of new pressure expansion technology that was released by Burr OAK Tool Inc. (BOTI) in November 2015 [16]. Also, a joint white paper from Optimized Thermal Systems (OTS) and BOTI reported on the effects of manufacturing methods on tube enhancements [17].

One of the highlights of the 2016 Purdue Conferences was a paper on noninvasive pneumatic pressure expansion, which provided the latest test results on this important new manufacturing method [18]. The challenges of applying bullet methods to expand smaller diameter tubes was outlined and compared with alternative methods such as Limited Shrink Tension Expansion, Zero Shrink Tension Expansion and Tubular Hydro Expansion (Figure 7).

The new pressure expansion equipment from BOTI uses high pressure air as the expansion fluid. Noninvasive pressure expansion is inherently a zero shrink process. The Lévy-Mises equations that describe plastic flow in material show that a tube experiences zero axial strain while pressure is applied to expand the tube diameter plastically. The internal pressure that expands the tube diameter also places the tube in tension; and, in fact, the tension is the exact amount needed to keep the tube from shrinking.

This approach allows for quick filling of the tubes while maintaining the cleanliness of the coils. The use of water or other liquids would require post-process cleaning, which is undesirable in the manufacture of coils for air-conditioners.

Coils made using mechanical methods were compared with coils made using the new pressure expansion method with respect to visual inspection, physical testing of heat exchanger strength and construction, measurement of heat exchanger dimensions, and physical testing of heat transfer performance. Most strikingly, the pressure expansion resulted in more consistent expansion of the tubes. The standard deviation of the final tube diameter was only 0.016 mm for the pressure expanded coils compared to 0.029 for the mechanically expanded coils (Figure 8).

The pressure expansion method allows for damage free internal enhancements; improved contact between the tubes and the fin collars; and better control over the final dimensions of the tubes.

The use of high pressure air for tube expansion provides a level of quality control by identifying any defective

tubes early in the manufacturing process before subsequent brazing and leak testing. The equipment was designed with multiple safety features as described in a recent video from Burr Oak Tool Inc. which can be viewed on the Burr Oak Tool YouTube channel. Furthermore, a new white paper is now available from Burr Oak addressing the issue of safety [19].

Summary and Conclusion

The design of appliances using smaller diameter copper tubes has never been easier than it is now. Advances in airside and tube side simulations allows for coil designs to be optimized without having to build a single coil. The prediction correlations are better than ever and include tube correlations for smaller diameter copper tubes with a variety of tube enhancements and for many refrigerants. Manufacturing also is becoming easier with improved manufacturing methods offering improved throughput and reliability.

These advances are just in time as the industry begins to replace high-GWP refrigerants with low-GWP and ultralow GWP refrigerants, necessitating a reduction in refrigerant volume due to considerations about cost and flammability. The smaller diameter copper tubes allow for refrigerant volumes to be reduced without compromising energy efficiency and other advantages such as cleanability, drainage and ease of manufacturing. **IAM**

References

Note: "Purdue 2016" refers to the 16th International Refrigeration and Air Conditioning Conference at Purdue, July 11-14, 2016.

1. Shekhar Sarpotdar, Dennis

Nasuta, Vikrant Aute, "CFD Based Comparison of Slit Fin and Louver Fin Performance for Small Diameter (3 mm to 5 mm) Heat Exchangers" Purdue 2016, Paper 2362.

2. Shekhar Sarpotdar, Dennis Nasuta, Vikrant Aute, "CFD-Based Airside Heat Transfer and Pressure Drop Correlation Development for Small Diameter (3 mm to 5 mm) Louver Fin Heat Exchangers," Purdue 2016, Paper 2363.

3. Nigel D. Cotton, Bob Weed and Wenson Zheng, "Building Better Appliances with Smaller Diameter Copper Tubes," International Appliance Manufacturing, October 2013.

4. For information on CoilDesigner®, visit the CoilDesigner webpages of CEEE at www.ceee.umd.edu/consortia/isoc/coil-designer; and OTS at www.optimizedthermalsystems.com.

5. MicroGroove Update, "In the Spotlight: Professor G.L. Ding," Vol. 2, No. 3, June 2012. www.microgroove.net/microgroove-update-newsletter

6. Simone Mancin, Claudio Zilio, Giulia Righetti, Luca Doretti, Giovanni A. Longo, "R134a Flow Boiling inside a 4.3 mm ID Microfin Tube," Purdue 2016, Paper 2265.

7. Giovanni A. Longo, Simone Mancin, Giulia Righetti, Claudio Zilio, "HFO1234ze(E) and HFC134a Flow Boiling Inside a 4mm Horizontal Smooth Tube," Purdue 2016, Paper 2167.

8. Norihiro Inoue, Daisuke Jige, Kentaro Sagawa, "Evaporation Heat Transfer and Pressure Drop of R32 inside Small-diameter 4.0 mm Tubes," Purdue 2016, Paper 2394.

9. Shingo Nakamura, Chieko Kondou, Nobuo Takata, Shigeru Koyama, "Comparison on Evaporation Heat Transfer between R32/R1234yf and R32/R1234ze(E) Flowing in Horizontal Microfin Tubes," Purdue 2016, Paper 2244.

10. Cichong Liu, Ziyang Sun, Ziqi Zhang, Junye Shi, Jiangping Chen, "Review of Condensation and Evaporation of R290," Purdue 2016, Paper 2413.
11. Yoram Shabtay, Jian Yu, Nigel Cotton, "New copper-tube technologies for heat exchangers: R290 condenser coil and R744 gas cooler," Light Commercial Refrigeration Panel, 2016 ATMOSphere America, Chicago, Illinois.
12. Zhan F L, Ding G L, Zhao F F, et al., "A Review of Researches on Long-term Performance Degradation of Heat Exchangers in Air Conditioners [J]," Journal of Refrigeration, 2015, Volume 36, Number 3, pp. 17-23.
13. Tao Ren, Guoming Wu, Guoliang Ding, Xinqiao Jin, Yongxin Zheng, Yifeng Gao and Ji Song, "Simulation and Application of 5 mm Tube Condenser in Display Cabinet," Fourth IIR conference on sustainability and the cold chain, Auckland, New Zealand, 2016.
14. Daniel Bacellar, Vikrant Aute, Reinhard Radermacher, "Wavy Fin Profile Optimization Using NURBS for Air-To-Refrigerant Tube-Fin Heat Exchangers with Small Diameter Tubes," Purdue 2016, Paper 2119.
15. Daniel Bacellar, Vikrant Aute, Reinhard Radermacher, "CFD-Based Correlation Development for Air Side Performance of Wavy Fin Tube Heat Exchangers using 2mm-5mm Tube Diameters," Purdue 2016, Paper 2120.
16. Nigel Cotton and Yoram Shabtay, "Trends in the Design and Manufacture of Round-Tube Plate-Fin Coils from Smaller Diameter Copper Tubes," International Appliance Manufacturing, October 2015.
17. "A Review of the Influence of Microfin Enhancements on the Condensation Heat Transfer

- Coefficient for Small Diameter Tubes," unpublished report from OTS and Burr Oak Tool Inc., 2015. Available on microgroove.net.
18. Roger Tetzloff, Vikrant Aute, Song Li and Cara Martin, "Evaluation of a Pressure Expansion Method for the Manufacturing of Copper Tube

- Heat Exchangers," Purdue 2016, Paper 2532.
19. Burr OAK Tool Inc., "Pressure Expansion Equipment – Risk Assessment and Risk Mitigation," Phoenix Expansion Equipment Digital Whitepaper, 2016. Download from Burr OAK Tool Inc. www.burroak.com.

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