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Roger Tetzloff
Burr Oak Tool, Inc., Sturgis, MI, USA, rtetzloff@burroak.com

Vikrant Aute
Center for Environmental Energy Engineering, University of Maryland College Park, vikrant@umd.edu

Song Li
Optimized Thermal Systems, Inc., United States of America, li@optimizedthermalsystems.com

Cara Martin
Optimized Thermal Systems, Inc., United States of America, cmartin@optimizedthermalsystems.com

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An Evaluation of a Pressure Expansion Method for the Manufacturing of Copper Tube Heat Exchangers

Roger TETZLOFF[1]*, Vikrant AUTE[2], Song LI[3], Cara MARTIN[3]

[1]Burr Oak Tool, Inc.,
Sturgis, MI, USA
(269-651-9393 x281, rtetzloff@burroak.com)

[2]University of Maryland College Park, Center for Environmental Energy Engineering,
College Park, MD, USA
(301-405-8726, vikrant@umd.edu)

[3]Optimized Thermal Systems, Inc.
Beltsville, MD, USA
(866-485-8233 x33, li@optimizedthermalsystems.com)
(866-485-8233 x27, cmartin@optimizedthermalsystems.com)

* Corresponding Author

ABSTRACT

The need for energy efficient, low cost, and reduced material solutions are encouraging HVAC&R engineers to explore new heat exchanger designs, including those using small diameter tubes and tubes with internal enhancements. Such developments thus require review and consideration for new and/or improved heat exchanger manufacturing techniques. Experimental and analytical study of a pressure expansion approach as compared to the more conventional mechanical expansion process was conducted to evaluate the impact of manufacturing method on heat exchanger performance. This included visual inspection and comparison of heat exchangers manufactured using pressure expansion and mechanical expansion, physical testing of heat exchanger strength and construction, measurement of heat exchanger dimensions, and physical testing of heat transfer performance.

Multiple heat exchangers were constructed and evaluated using both the mechanical and pressure expansion methods. Consistency between coils was maintained in order to isolate the manufacturing method, to the extent possible, for comparison purposes. Visual inspection of compared coils and past research suggest that pressure expansion improves the contact between the expanded tube and the fin, providing the potential to improve heat transfer performance. Visual inspection also suggests that pressure expansion produces less deformation of any internal tube enhancements, maximizing the potential to improve heat transfer performance from the use of such tubes.

Physical measurements of the tube expansion diameter throughout the construction of a heat exchanger expanded using the pressure expansion process proved that the pressure expansion method delivers a more consistent tube diameter. Air-side testing using water as refrigerant also confirmed that overall heat transfer performance for pressure expanded coils is, at minimum, consistent with that for mechanically expanded coils.

1. INTRODUCTION

Round Tube Plate Fin (RTPF) heat exchangers are used extensively within the HVAC industry. Small diameter Microgroove tubing is increasing in use in order to meet requirements for increased heat transfer, higher efficiencies, and the use of low global warming potential (GWP) refrigerants. The trend for increasingly smaller diameter tubes presents a challenge to conventional processes used in joining these tubes to heat exchanger fins. A comprehensive comparison between conventional and pressure expansion manufacturing methods was conducted in order to assess the potential for developing small diameter Microgroove RTPF heat exchangers more reliably and with less failure.

1.1 Conventional Expansion Method and Challenges with Small Diameter Heat Exchangers

The manufacturing process of RTPF coils creates a rigid assembly from parts that are individually rather delicate. Small diameter tubes have higher strength for resisting internal pressure. However, when not assembled into a coil, the tubes' small diameter makes them weaker in resisting bending and buckling. The joining of tubes and fins is what makes the assembly strong. In addition, the joint between the tube and fin creates a path for heat conduction. If improperly joined, the boundary left between the tube and fin can become a barrier to heat transfer. Mehendale et al. (2013, 2014) has further found that mechanical expansion can reduce the overall heat transfer performance (UA) of a coil.

The combination of high strength to resist internal pressure and lower buckling strength makes traditional joining processes more difficult for small diameter tube assemblies. The preferred method for joining tubes and fins is through a process of tube expansion to generate an interference fit between the tube and the extruded fin collar. This expansion is typically performed using a spherical "bullet" that is pushed through the tube by a smaller diameter rod, as shown in Figure 1.a. The bullet diameter is larger than the original tube inside diameter and thus causes the tube to expand. As the tube expands in diameter, material along the length of tube is drawn into the increased circumference of the tube. Consequently, the tube shrinks in length during the expansion process. Friction between the tube and bullet induces column loading on the tube causing it to buckle if not contained. Due to the high column loading of increasingly slender tubes, scrap rates from the expansion process due to compromised, defective and weakened tubes can be as high as 5-10%.

Another difficulty for producing smaller diameter tube coils is creating the bell and flare for return bend assembly at the open ends of the small diameter tubes. The bell and flare are usually formed within the bullet expansion process. The maximum elongation of the tube material is a limiting factor (typically 40-50 % for copper). When maximum material elongation is exceeded, splits occur in the tube flare and bell form. As the tube diameter decreases, the material elongation needed to make the flare is increased. In addition, as diameters decrease, the tube stickout variation in the manufacturing process has greater impact on the ability to produce a good flare. Tube stickout changes the relative positions between the end of tube and the bell/flare tools and is caused by variance in hairpin length. Scrap and rework due to poor flare processing of small diameter tube coils is significant.

1.2 Alternate Expansion Methods

1.2.1 Tension Expansion. Early adopters of small diameter tubes faced difficulties in the expansion process due to buckling of the tubes. This led to the development of "limited-shrink" expansion, which enabled successful expansion by placing the tube in tension to prevent buckling and to control shrinkage. Tension expansion, depicted in Figure 1.b., has been available for decades and is used for "progressive expansion machines" used to process low volume coils. These machines allow flexible production but require pre-processing of the tube flare for using a collet mechanism to grip the tube ends. Note that the tube is placed in tension as the expansion bullet is pushed through the tube. This is in contrast to the process of compression expansion, described above. Because the tube is in tension while expanding, there is less tube shrinkage during the expansion process, and tube buckling is eliminated, ultimately resulting in material savings. Limited Shrink Tension Expansion, shown in Figure 1.c., is a modification aimed at further decreasing the level of shrinkage of the tube. A hairpin clamp mechanism is incorporated into the process to apply additional force on the coil. With adequate bullet lubrication and the proper balance of bullet friction force and tube tension, the process will sometimes allow zero shrinkage of the tube.

1.2.2 Non-Invasive Zero Shrink Tension Expansion. Tubular Hydro-Expansion, shown in Figure 1.d., is another existing process used within the HVAC industry to expand coils. The method is used extensively in baseboard heater coil manufacturing where water is injected into the tube and pressurized to cause the tube to exceed its yield strength and expand into the fins, thereby creating a strong mechanical bond between the tube and fins. Hydroforming is used extensively in the tube processing industry with various fluids such as water, oil, and gasses. It should be noted, however, that processing coils using water as an expansion medium can create problems in most air-conditioning applications due to incompatibility with commonly used refrigerants.

The process of expansion using pressure behaves according to well-understood models of cylindrical pressure vessels. Pressure expansion is inherently a zero-shrink process. Lévy-Mises equations describing plastic flow in material can be used to show that a tube experiences zero axial strain while pressure is applied to expand the tube diameter plastically. In effect, the internal pressure that causes hoop stress in the tube resulting in expansion of the tube diameter also places tension on the tube, in the precise amount needed, to prevent the tube from shrinking. An assumption made in the plastic flow model is that tube material properties are isotopic. However, the tube straightening process incorporated when making hairpins used in coil construction influences axial material properties differently than radial properties, thereby causing the tube to shrink during expansion. In addition, when the tube expands to meet the fin collar, both the tube and fin collar expand further with added internal pressure. During this phase of coil expansion, the hoop strength of the fin collar resists further expansion but the axial strength of the tube/fin combination does not increase significantly due to the segmented nature of the fin collars. The combined effect is that the tube experiences initial shrinkage in length followed by growth when the tube engages the fins. Inability to control the growth of the coil limits the process from achieving maximum expansion diameter, causes high process coil length variability, and potentially leads to gaps between fin collars as the tubes grow in length.

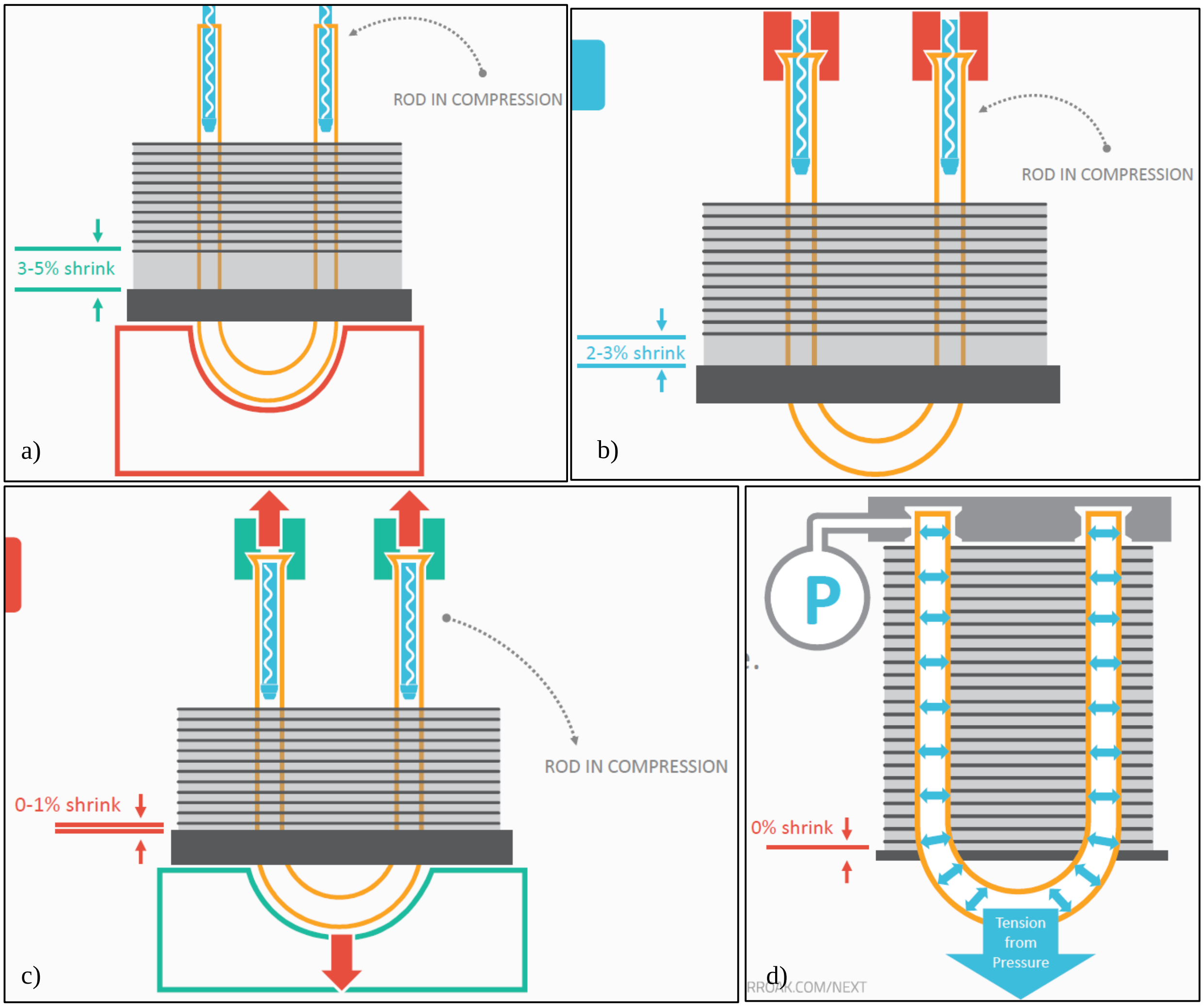

Figure 1: a) Conventional Compression Expansion; b) Tension Expansion; c) Limited Shrink Tension Expansion; and d) Zero-Shrink Tension Expansion

1.2.3 Pressure Expansion. A new pressure expansion method has been developed that addresses many of the inherent challenges of existing manufacturing processes specifically for the use with small diameter coils. In this approach, the open ends of each tube in a coil are clamped and sealed simultaneously. High pressure air is used as the expansion fluid for quick filling of the tubes and to maintain cleanliness of the coils, as opposed to using water or other liquids that would necessitate post process cleaning. In fact, the process is credited for the ability to flush debris from the coil in some instances. The pressurization parameters of the process are key to controlling the accurate expansion diameter. Servo control of the pressure sequence, timing, and exact pressure setting determines the final expanded diameter. As described above, the tubes in the coil both shrink and grow in length when expanded with pressure. The new pressure expansion method controls the coil length by containing the tube hairpin ends in precisely controlled receiver nests. This allows high process control of coil length and expansion diameter and provides high quality contact between the tubes and fin collars.

2. EVALUATION OF COILS DEVELOPED WITH THE PRESSURE EXPANSION METHOD

A number of evaluations were conducted to assess the potential and performance of the new pressure expansion method for use with small diameter RTPF coils. Assessments included inspection of the tube expansion diameter, effectiveness of developing a good tube-fin contact, visually inspecting the impacts on the internal Microgroove geometry and physically measuring the heat transfer performance.

2.1 Expansion Diameter

Measuring the expanded diameter of pressure expanded coils can be accomplished through destructive measurement, removing the fins from the tubes and then measuring the tube diameter, or by non-destructive measurement using a measuring microscope to determine the expanded fin collar diameter. For this study, a measuring microscope was used to measure the expanded fin collar at three locations along the length of each of the expanded tubes within a coil. As shown in Table 1 and histograms presented in Figure 2, results for the pressure expanded coil resulted in more consistent expansion, with a standard deviation nearly half that as measured for the mechanically expanded coil.

Table 1: Measurement results for expansion diameter for pressure and mechanically expanded coils

Parameter	**Pressure Expansion Coil Results**	**Mechanical Expansion Coil Results**
Average Expanded Tube Diameter	5.254 mm (0.20683 inches)	5.248 mm (0.20662 inches)
Minimum Measurement	5.227 mm (0.2058 inches)	5.164 mm (0.2033 inches)
Maximum Measurement	5.301 mm (0.2087 inches)	5.298 mm (0.2086 inches)
Measurement Range	0.074 mm (0.0029 inches)	0.135 mm (0.0053 inches)
Measurement Standard Deviation	0.016 mm (0.00061 inches)	0.029 mm (0.0116 inches)

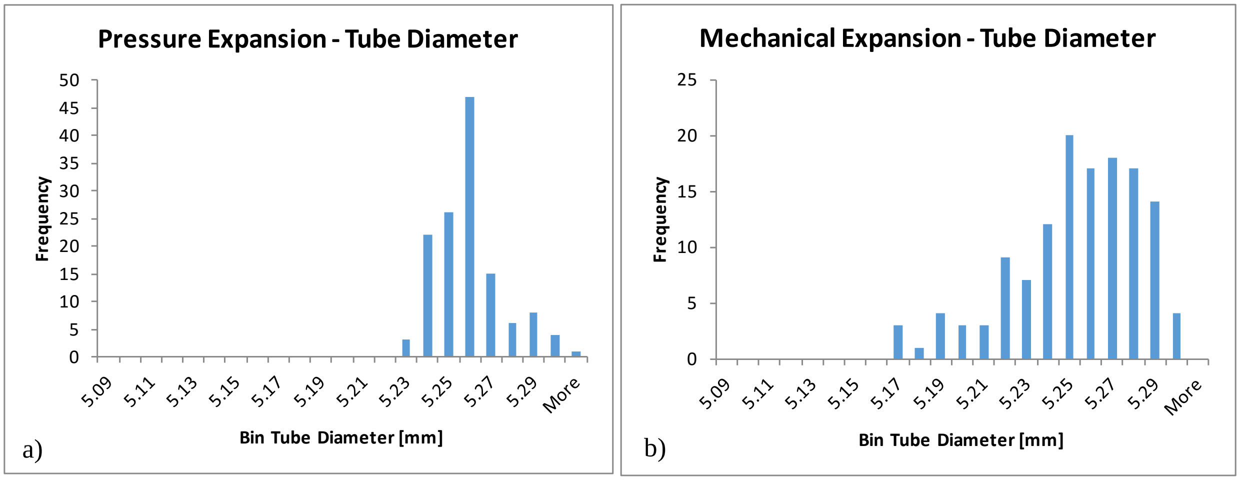

Figure 2: a) Tube expansion diameter measurements for pressure; and b) mechanically expanded coils

2.2 Tube-Fin Contact

The coil expansion process relies on dissimilar material properties between the tube and fin to generate an interference fit between the outside-tube-diameter and the fin-hole-diameter. Copper tube material is generally soft prior to expansion and behaves plastically. When the tube expands it remains expanded. The aluminum fin material is generally much harder and behaves elastically during the expansion process. The fin collar acts as a spring around the tube, as shown in Figure 3 and 4. If it were possible to disassemble and then measure the fins and tubes after expansion, one would observe that the fin-hole-diameter is smaller than the outside-tube-diameter.

As noted above, the joining of tubes and fins is what makes the coil assembly strong. In addition to creating a rigid assembly, the joint between the tube and fin creates a path for heat conduction. Evaluation of this joint by sectioning, clearly illustrates the superior nature of the tube/fin bond using pressure expansion when compared to bullet expanded coils. Figure 3 compares identical coils, one pressure expanded (Figure 3.a.), and the other expanded using conventional bullet expansion (Figure 3.b.). In the case of the bullet expanded coil, significant compressive loading on the fins created disruptions in the tube/fin bond. Numerous studies have investigated and determined significant heat transfer degradation due to improper bonding caused by bullet expansion (Tang et al., 2011). The pressure expansion process provides superior consistency in the tube/fin bond.

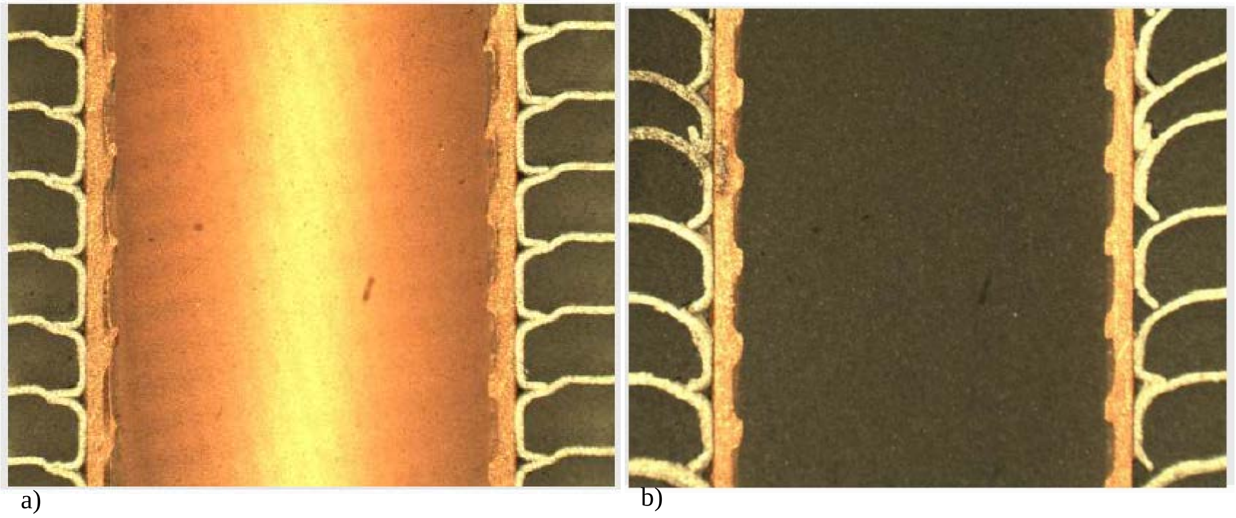
a) b)

Figure 3: a) Tube-Fin Contact for pressure expanded coil; and b) mechanically (bullet) expanded coil

2.3 Internal Enhancement Visualization

A significant advantage of using pressure to expand tubes is that the internal tube enhancements are not disturbed as they are using a mechanical bullet. This comparison is illustrated in images of small diameter internally enhanced Microgroove tubes, such as that shown in Figure 4. For the bullet method (Figure 4.b.), the stresses exerted on the internal enhancements of the tube are significant. The bullets flatten the tops of certain types of inner fins and they preclude the use of other types of enhancements. Expanding tubes with pressure enables tube manufacturers and researchers to explore new possibilities in enhancement design for features that would otherwise be removed by the bullet expansion process.

2.4 Heat Transfer Testing

In order to assess the impact of pressure expansion on coil heat transfer performance, a set of identical coils save for the difference in manufacturing method (either conventional mechanical or pressure expansion) were tested in a temperature controlled wind tunnel.

2.4.1 Experimental Set-up. Coils were installed in a 2’ x 2’ square temperature-controlled wind-tunnel, which was constructed according to ASHRAE Standard 41.2 [1], and it is connected to a water loop, as shown in Figure 4. Coil inlet air was first conditioned by the loop’s air handling unit (AHU) and temperature and air flow rate were maintained at set conditions. Air dry-bulb temperature was measured using a 9-point thermocouple grid at multiple points throughout the test section including prior to an array of industry-grade nozzles that measured the actual air flow rate, and just before and after the tested coil. A differential pressure sensor was used to measure the pressure drop before and after the coil.

A water loop was constructed to feed hot water into the coil to test under condensing conditions. Hot water was generated by a heat pump water heater. Water was recirculated between a warm water tank (buffer tank) and the water heater to keep the water at a set temperature. A pump coupled with variable frequency drive (VFD) maintained a steady water flow rate into the test coil. A pair of resistance temperature diodes (RTDs) were installed before and after the coil to measure water inlet and outlet temperatures. A Coriolis flow meter measured the actual water flow rate. In order to control the entering water temperature, a mixing valve was used to mix the returning water and hot water from the water tank to achieve the desired inlet water temperature.

A listing of measurement devices and their respective accuracy is provided in Table 2. A schematic of the test layout is shown in Figure 5.

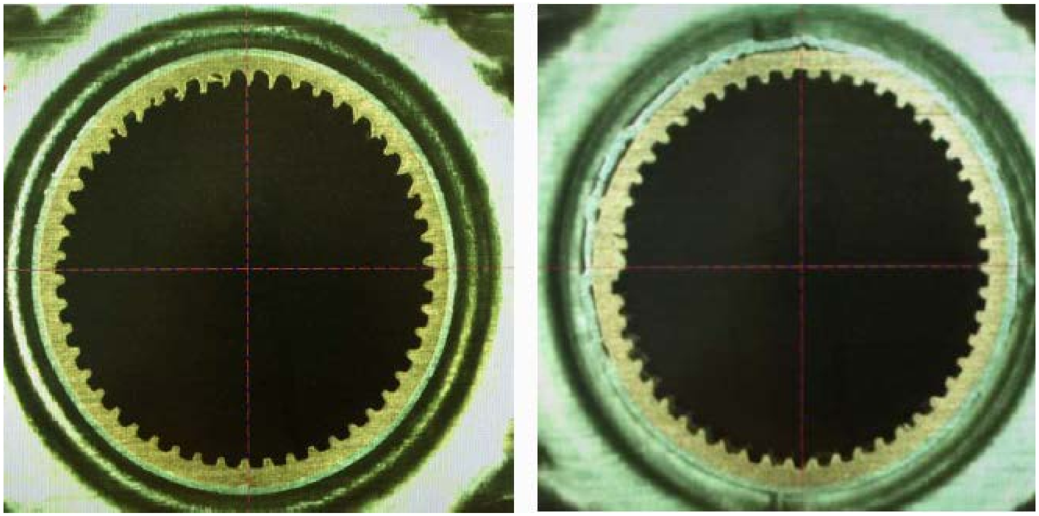
a) b)

Figure 4: a) Internal tube enhancements for pressure expanded tube; and b) mechanically (bullet) expanded tube

Table 2: Test Instrumentation

Parameter	Instrument	Sensor Model No.	Range	Accuracy
Air-side Temperature	Thermocouple	Omega TT-T-24-SLE-100	-200 to 200°C	+/- 0.5°C
Water Inlet/outlet Temperature	RTD	Omega P-M-1/10-1/4-6-0-P-15	-100 to 400°C	+/- 0.03°C
Water Flow Rate	Coriolis Flow Meter	MicroMotion CMFS025M319N2BAEKZZ	0-50 g/s	+/- 0.4g/s
Nozzle Pressure Drop	Differential Pressure Transducer	Omega PX274-05DI	0-1244 Pa	+/- 12.4 Pa
Coil Air-side Pressure Drop	Differential Pressure Transducer	Omega PX277-01D5V	0-62 Pa	+/- 0.6 Pa

2.4.2 Experimental Approach. Coils with 5 mm and 7 mm outer diameter were constructed for testing. A total of eight 7mm coils, as noted in Table 3, and thirteen 5mm coils, as noted in Table 4, were tested. Each coil was tested at three different air flow rates, and a fixed incoming air temperature (10°C), water flow rate (40 g/s) and water inlet temperature (35°C), as shown in Table 5.

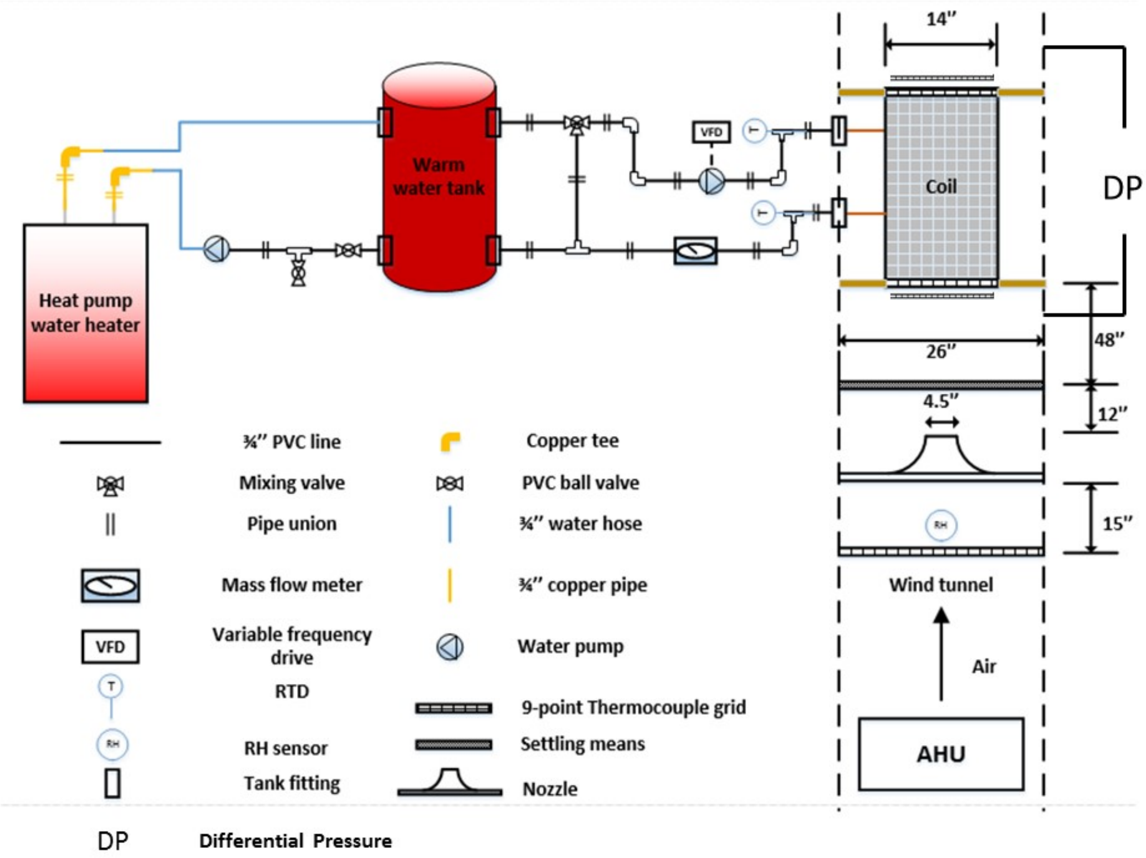

Figure 5: Test Schematic

Table 3: 7 mm Coil Specification

Coil	Expansion method	Expansion diameter	Fin material	Fin splits (%)	Fin die manufacturer
1.2	Bullet	7.450 mm (0.2933 inches)	H22	0.00	2
2.1	Pressure	7.585 mm (0.29864 inches)	H22	3.39	2
3.1	Pressure	7.408 mm (0.29167 inches)	H22	0.00	2
10.1	Bullet	7.518 mm (0.29599 inches)	H22	0.00	2
11.1	Pressure	7.372 mm (0.29024 inches)	H22	0.03	2
12.1	Pressure	7.417 mm (0.29199 inches)	H22	0.01	2
13.1	Pressure	7.464 mm (0.29385 inches)	H22	0.03	2
14.1	Pressure	7.443 mm (0.29304 inches)	H22	0.00	2

Table 4: 5 mm coil specifications

Coil	**Expansion method**	**Expansion diameter**	**Fin material**	**Fin splits (%)**	**Fin die manufacturer[1]**
1.1	Bullet	5.248 mm (0.20661 inches)	H22	0.00	1
2.2	Pressure	5.225 mm (0.20569 inches)	H22	0.00	1
3.2	Pressure	5.314 mm (0.20923 inches)	H22	0.63	2
4.2	Pressure	5.249 mm (0.20665 inches)	H25	0.00	2
5.1	Pressure	5.339 mm (0.21018 inches)	H22	0.59	2
6.2	Pressure	5.25 mm (0.20669 inches)	H25	0.06	2
7.2	Pressure	5.402 mm (0.21268 inches)	H25	2.93	2
8.1	Pressure	5.489 mm (0.2161 inches)	H22	11.46	1
9.1	Bullet	5.374 mm (0.21159 inches)	H22	0.01	1
10.1	Bullet	5.316 mm (0.20929 inches)	H25	0.00	1
11.1	Pressure	5.316 mm (0.20928 inches)	H25	0.00	1
12.1	Pressure	5.294 mm (0.20843 inches)	H25	0.00	1
13.1	Pressure	5.258 mm (0.20701 inches)	H25	0.00	1

Table 3: 5 & 7 mm Coil Test Matrix, Dry Air

Test	Air flow rate	T air in (^oC)	Water flow rate (g/s)	T water in (^oC)
1	0.163 m^3/s (350 CFM)	10	40	35
2	0.267 m^3/s (550 CFM)	10	40	35
3	0.350 m^3/s (750 CFM)	10	40	35

2.4.3 Data Reduction and Analysis. Using the measurements collected as noted in Figure 4, total heat load and heat transfer coefficient were calculated according per Equations 1 through 7.

$$Q_{water} = \dot{m_{water}} * CP_{water} * (T_{water_{in}} - T_{water_{out}}) \tag{1}$$

$$\dot{m_{air}} = VFR_{air} * \rho_{air} \tag{2}$$

$$Q_{air} = \dot{m_{air}} * CP_{air} * (T_{air_{out}} - T_{air_{in}}) \tag{3}$$

$$\Delta T_a = T_{water_{in}} - T_{air_{out}} \tag{4}$$

$$\Delta T_b = T_{water_{out}} - T_{air_{in}} \tag{5}$$

$$LMTD = (\Delta T_a - \Delta T_b)/(\ln\left(\frac{\Delta T_a}{\Delta T_b}\right)) \tag{6}$$

$$UA = Q_{water}/LMTD \tag{7}$$

Where:

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[1] Two different fin manufacturer dies were used in the evaluation. Names have been omitted here for confidentiality.

Q: heat load (kW)
$\dot{m}$: mass flow rate (kg/s)
CP: specific heat (kJ/kg*K)
T: temperature (^{o}C)
VFR: volume flow rate (m^3/s)
ρ: density (kg/m^3)
$LMTD$: log mean temperature difference (K)
UA: heat transfer for given area (kW/K)

2.4.4 Heat Transfer Test Results. Based on the experimental test, UA values obtained were normalized with respect to actual air velocity across each coil, and the comparisons are demonstrated in Figure 6. Under similar test conditions, there is no significant difference in UA values between the two expansion methods. It should be noted that there was a slight variation in air-side pressure drop among the different coils, and this was partially caused by small difference in air flow rate through each coil, as well as inconsistency in fin density and manufacturing inconsistency.

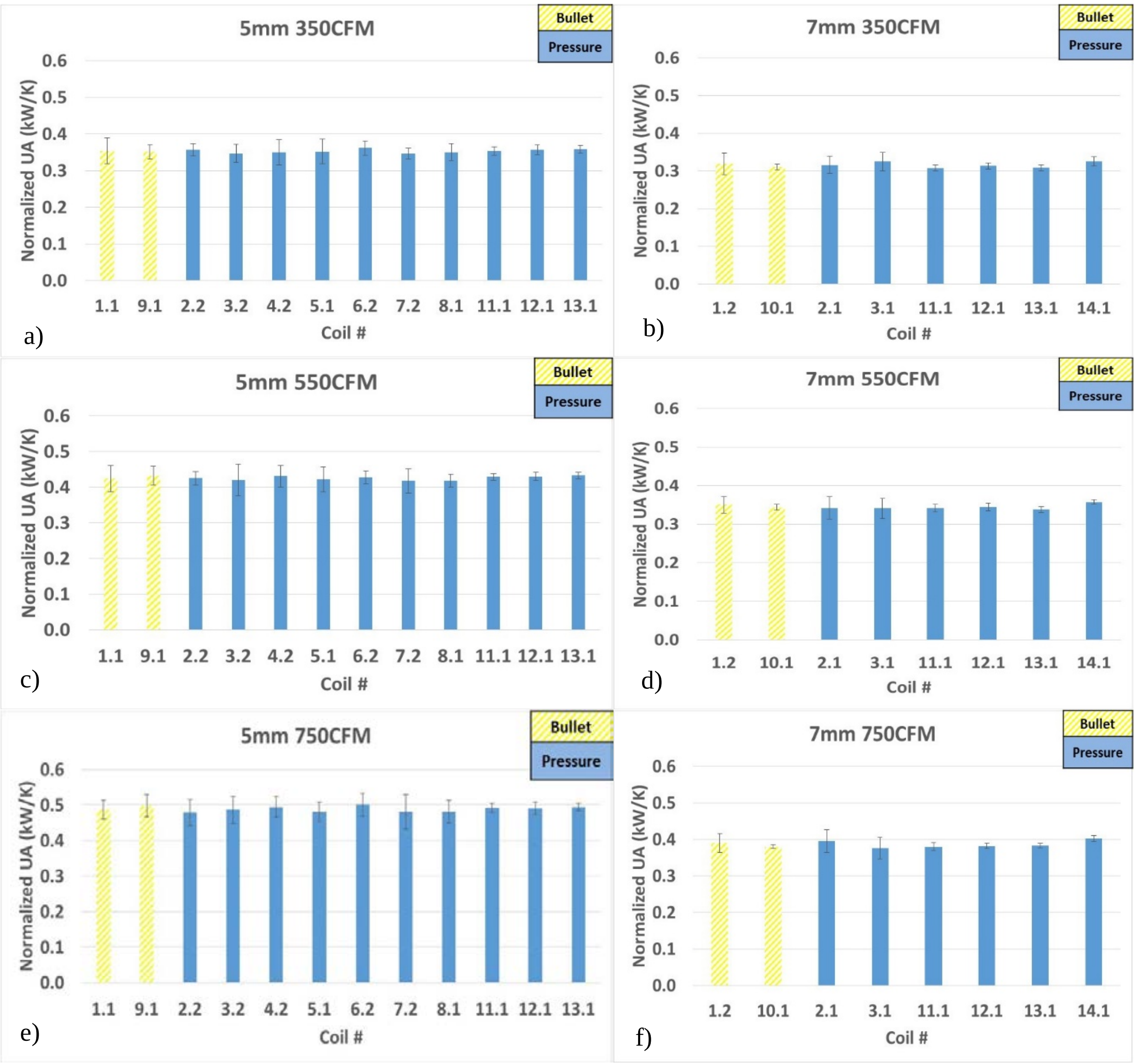

Figure 6: Normalized Results for a) 5 mm at 350 CFM b) 5 mm at 550 CFM c) 5 mm at 750 CFM d) 7 mm at 350 CFM e) 7 mm at 550 CFM and f) 7 mm at 750 CFM

3. CONCLUSIONS

Based on a series of physical measurements, visual inspections, and coil tests, the new pressure expansion method shows significant improvements and potential over more traditional mechanical expansion processes. Measurements of tube diameter show that pressure expanded coils have a more consistent expanded diameter than their mechanically expanded counterparts. Close visual inspections using advanced microscopy indicate not only a better tube-fin contact, but less damage of internal tube enhancements for pressure expanded tubes and coils. Furthermore, the pressure expansion method maintains, and has the potential to improve, overall heat transfer performance for a coil, as compared to the traditional mechanical expansion (bullet) method. Given the range in heat transfer improvement (1 – 7%) that was observed, depending on the coil and method evaluated, a definitive improvement cannot be concluded. This order of magnitude improvement is within the range for manufacturing uncertainty, i.e. coil-to-coil variation or even manufacturer-to-manufacturer variation. A larger sample size is needed to evaluate whether this level of improvement is due to the manufacturing method alone. Two phase heat transfer coefficient and pressure drop tests on pristine and expanded tubes is also required to fully characterize this improvement.

NOMENCLATURE

AHU	Air Handling Unit	
CP	Specific Heat	kJ/kg*K
CFM	Airflow, Cubic Feet per Minute	ft^3/min
DP	Differential Pressure	
GWP	Global Warming Potential	
HVAC&R	Heating, Ventilation, Air Conditioning and Refrigeration	
LMTD	Log Mean Temperature Difference	K
$\dot{m}$	Mass Flow Rate	kg/s
ρ	Density	kg/m^3
Q	Heat Load	kW
RH	Relative Humidity	%
RTD	Resistance Temperature Diode	
RTPF	Round Tube Plate Fin	
T	Temperature	(°C)
ΔT	Temperature difference	
UA	Heat Transfer Per Given Area	kW/K
VFD	Variable Frequency Drive	
VFR	Volume Flow Rate	m^3/s

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