2022

3 and 5mm Copper Tube Fin Heat Exchangers: Continued Testing and Frost Developing Characteristics

Dennis Michael Nasuta

Song Li

Regina Hong

3 and 5mm Copper Tube Fin Heat Exchangers: Continued Testing and Frost Developing Characteristics

Dennis NASUTA*[1], Song LI[1], Regina HONG[2]

[1]Optimized Thermal Systems, Inc.
Beltsville, MD, USA
nasuta@optimizedthermalsystems.com

[2]OTS Energy
Knoxville, TN, USA
regina.hong@otsenergy.com

* Corresponding Author

ABSTRACT

The inverse relationship between tube diameter and compactness is well-established in tube-fin heat exchangers. For multiple decades, designers have implemented smaller-diameter tubes in heat exchangers (HXs) as a solution to improve performance, reduce refrigerant charge, and reduce cost. While products with 5mm OD tubes have become prevalent in the industry, diameters less than 5mm remain uncommon. A question remains: are further reductions in tube diameter worthwhile? Past work has demonstrated that 3mm copper tube and aluminum fin designs are capable of considerable improvements in thermal-hydraulic performance, compactness, and material utilization. These optimized designs were verified with first-in-kind 3mm tube-fin prototypes that were tested experimentally and compared with equivalent 5mm designs. While the findings confirmed the optimality of 3mm designs, the prototypes were not built exactly within specifications for FPI. In this work, new prototypes with slightly different dimensions were constructed and tested. The results again validate the accuracy of CFD-based correlations developed for 3-5mm OD tube-fin heat exchangers and demonstrate further performance advantage for the 3mm relative to 5mm baseline.

In addition to this validation, sample heat exchangers were tested in wet (dehumidification) conditions as well as lower temperature tests where frost formation occurred. Two copies of each 3 and 5mm coil were tested: an original baseline heat exchanger and an identical copy with a hydrophobic coating applied. This work compares differences in behaviors in wet and frosting conditions for the two tube diameter samples with and without coatings. Frosting test results showed more rapid frost formation of 3mm samples due primarily to the fact that they use a higher fin density than their 5mm counterparts. While this disadvantaged performance in frost-forming conditions may preclude their use in some refrigeration and heat pumping applications, test results also indicated that a coating may significantly extend the operating time of 3 and 5mm heat exchangers alike.

1. INTRODUCTION

The confluence of market forces, regulatory requirements, and increasing environmental concerns continue to push heat exchanger designs towards ever higher thermal performance while minimizing material costs and refrigerant charge. HVAC products have trended towards heat exchangers with smaller diameters and feature sizes as seen in the increasing adoption of 7mm and 5mm tube-fin heat exchangers along with microchannels as replacements for conventional larger diameter tube-fin designs. This recent acceptance of 5mm diameters came only after extensive R&D efforts in industry and academia confirmed the techno-economic feasibility of these HXs. Academic research continues to indicate increasing optimality in further reducing tube diameters with numerous theoretical and experimental studies demonstrating the performance of HXs with diameters less than 1mm (e.g. Bacellar et al., 2016; Radermacher et al., 2017). While some commercially available products do make use of such next generation heat exchangers, they have not yet found widespread acceptance in the HVAC industry due in large part to their manufacturing complexity and unproven reliability. It is then prudent to ask if further reducing the diameter of successful tube-fin HXs below 5mm can unlock further performance gains while remaining manufacturable, cost-effective, and reliable.

This work builds upon the body of research exploring the feasibility of such small diameter HXs. In past years, CFD-based correlations were developed to characterize the airside performance of 2-5 mm OD tube-fin HXs with plain, wavy, slit, and louvered fin surfaces (Bacellar, Aute, & Radermacher, 2016; Bacellar et al., 2014; Sarpotdar et al., 2016b, 2016a). Experimental validation of 16 slit and louver heat exchangers with 5mm diameters was presented in Nasuta et al. (2018). In 2021, work was presented summarizing the design, construction, and testing of the first published 3mm OD tube-fin HXs known to the authors (Bacellar et al., 2021). This previous work presented several key findings: First, a numerical study showed a 3mm HX could have 15% more capacity than a 5mm one for the same airside pressure drop (or 60% less pressure drop for the same capacity). However, since prototypes were not built with the designed FPI, the 3mm HXs fell slightly short of this expectation, but still achieved 5-10% better thermal-hydraulic ratio than their 5mm counterparts. The experimental results also served to validate the CFD-based correlations with average deviations of 2.8% in heat load and 14% in airside pressure drop.

This paper makes several additional contributions to further the understanding of 3mm OD tube fin HXs. First, a new set of prototypes were constructed, more similar to the originally selected designs. These heat exchangers were tested in dry conditions for comparison against one another as well as the airside correlation predictions. Additionally, tests were performed in both wet (dehumidifying) conditions and frost-developing conditions to provide initial data on the performance of 3mm HXs in these important operating modes.

2. MATERIALS AND METHODS

2.1 Prototypes

A total of seven prototype heat exchangers were fabricated for this effort. Three prototypes, denoted “original”, were used in the previous dry condition experimental validation (Bacellar et al., 2021) and were later subjected to frost condition tests in this work. Two copies of these, denoted “coated”, were produced with a superhydrophobic coating sprayed on the fin surfaces by the vendor and also subjected to frost testing and wet condition testing. Two final samples, denoted “new”, were produced with slightly adjusted fin density to better align with original design intentions. The basic characteristics of these sample HXs are described in Table 1 and photos are shown in Figure 1.

Table 1: Prototype Heat Exchangers

Coil:	**OD5 – Original**	**RD3 – Original**	**OD3 - Original**	
Tube OD [mm]	5	3	3	
FPI	17.4	26.8	20.0	
# Tubes	18	32	32	
Pt [mm]	12.9	8	9	
Pl [mm]	11.2	7	7.8	
A_o [m^2]	1.82	1.78	1.54	
Tube length [mm]	271	252	224	
Mass [kg]	0.72	0.52	0.46	
Test type	Dry*, Frost, Wet	Dry*, Frost, Wet	Dry*, Wet	
Coil:	**OD5 - Coated**	**RD3 – Coated**	**OD3 – New**	**OD5 – New**
Tube OD [mm]	5	3	3	5
FPI	17.4	26.8	23.9	17.2
# Tubes	18	32	32	18
Pt [mm]	12.9	8	9	12.9
Pl [mm]	11.2	7	7.8	11.2
A_o [m^2]	1.82	1.78	1.82	1.84
Tube length [mm]	271	252	224	277
Mass [kg]	0.72	0.52	0.50	0.73
Test Type	Frost, Wet	Frost, Wet	Dry	Dry

*These 3 dry test series are shown in Bacellar 2021 and are not included in this publication

All prototypes were fabricated with pressure-expanded tubes (as opposed to mechanical expansion). This process was expected to produce consistent prototypes with comparable tube-fin contact resistance. However, no measurements of fin collar quality or contact resistance were made, so any differences will become aggregated with the apparent airside heat transfer coefficient.

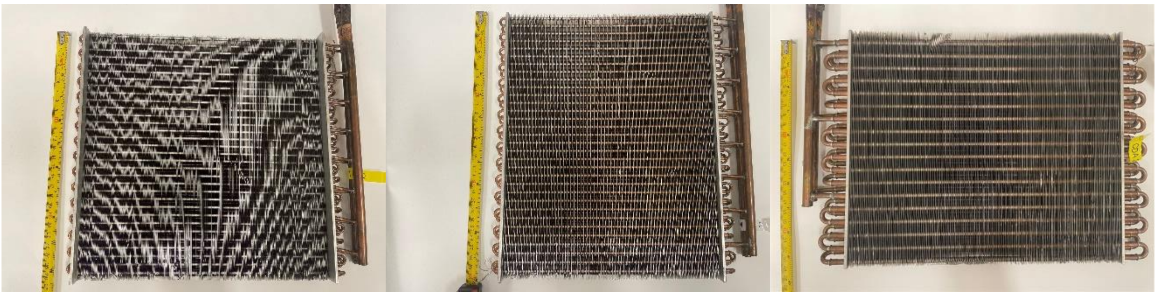
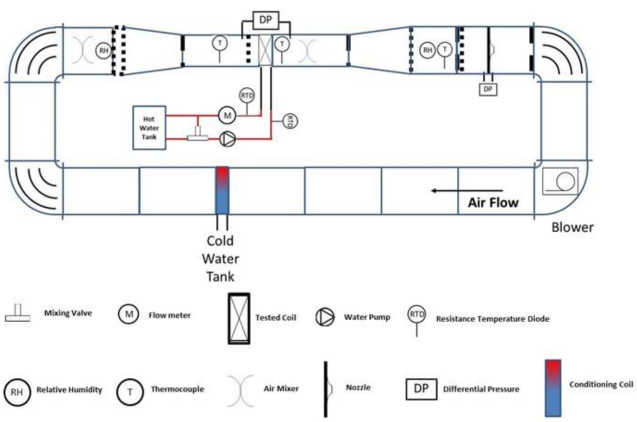


Figure 1: Prototypes (from left to right: RD3, OD3, OD5)

2.2 Experimental Facility and Methods

Tests were performed in the same temperature and humidity-controlled wind tunnel used in previous published work including Bacellar 2021. The schematic of the facility and key instrumentation details are shown in Figure 2. Inside the tubes, water was used as a working fluid in dry and wet condition tests while a water-propylene glycol mixture was used for frost tests. Energy balance errors in hot water tests were less than 3% and less than 10% in wet test conditions due to the high uncertainty introduced by relative humidity measurement.



Parameter	Type	Range	Systematic Uncertainty
Water flow rate	Coriolis flow meter	0 to 700 g/s	0.5% of reading
Water inlet & outlet temperature	RTD	-100 to 400°C	±0.03 K
Air inlet temperature	9-point thermocouple	-200 to 200°C	±0.17 K
Air outlet temperature	25-point thermocouple	-200 to 200°C	±0.1 K
Coil air-side pressure drop	Differential pressure	1" WC	0.25% FS
Relative humidity (RH)	RH sensor	0-95%	±2%
Nozzle air-side pressure drop	Differential pressure	5" WC	0.25% FS

Figure 2: Heat Exchanger Test Facility

In dry tests, data reduction was performed to calculate effective heat transfer coefficients from the measured capacity and LMTD. The water-side thermal resistance was calculated using Gnielinski's empirical correlation (1976). Along with the material conductivities and geometry, the effective HTC (which includes fin efficiency) can be determined as shown in the equations below:

$$UA = \frac{1}{R_{total}} = \frac{Q}{LMTD} = \frac{1}{R_{air} + R_{cond} + R_{water}} \tag{1}$$

$$R_{water} = \frac{1}{h_{water} A_{water}}, with\ h_{water} from\ Gnielinski\ (1976) \tag{2}$$

$$\eta_0 h_{air} = \frac{1}{A_{air}(R_{total} - R_{water} - R_{cond})} \tag{3}$$

3. RESULTS

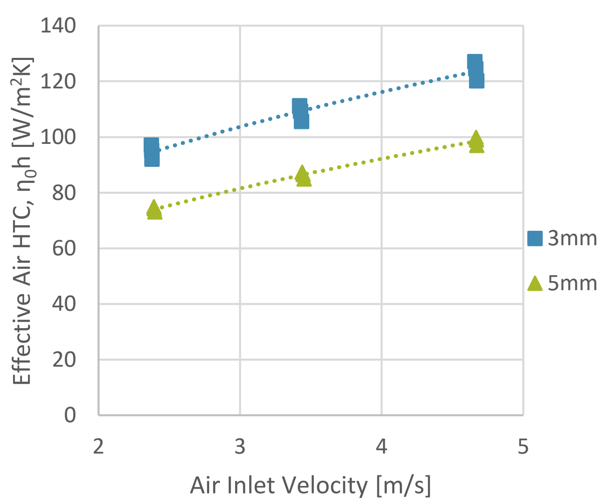
3.1 Hot Water (Dry-Condition) Testing

Typical procedures were followed to determine air-side heat transfer and pressure drop performance by testing the sample heat exchangers using hot water as the working fluid. These tests were performed with water flow rates high enough to ensure that the large majority of total thermal resistance was attributable to air-side convection, while the water-side convective heat transfer can be well-predicted with existing empirical correlations. In 2021, Bacellar published initial air-side performance data for the original three prototypes; this section outlines only the latest results from the most recent two prototypes: OD3-New and OD5-New. The test matrix describing temperatures and flow conditions is shown in Table 2.

Table 2: Hot Water Test Matrix for *OD3-New* and *OD5-New*

Test Number	Air Inlet Temperature [°C]	Water Inlet Temperature [°C]	Air Velocity [m/s]	Water mass flow rate [g/s]
1	20.0	50.0	2.3	75
2	20.0	50.0	2.3	100
3	20.0	50.0	2.3	125
4	20.0	50.0	3.3	75
5	20.0	50.0	3.3	100
6	20.0	50.0	3.3	125
7	20.0	50.0	4.5	75
8	20.0	50.0	4.5	100
9	20.0	50.0	4.5	125

Comparing the new 3mm and 5mm heat exchangers against one another, they have nearly identical airside surface area, but the 3mm design has 31% less mass, 30% less volume, and 47% less internal volume. Figure 3 shows two comparisons of dry air-side results for these samples (OD3-New and OD5-New). 9 tests were performed on each of the two samples but since only 3 unique air velocities were tested the points at different water flow rates appear overlaid. The 3mm design has an average heat transfer coefficient 20% higher than the 5mm design, while having an average air pressure drop 10% higher. The ratio of heat transfer to pressure drop, $\eta_0 hA/\Delta P$ averages 13% higher for the 3mm design than 5mm one.



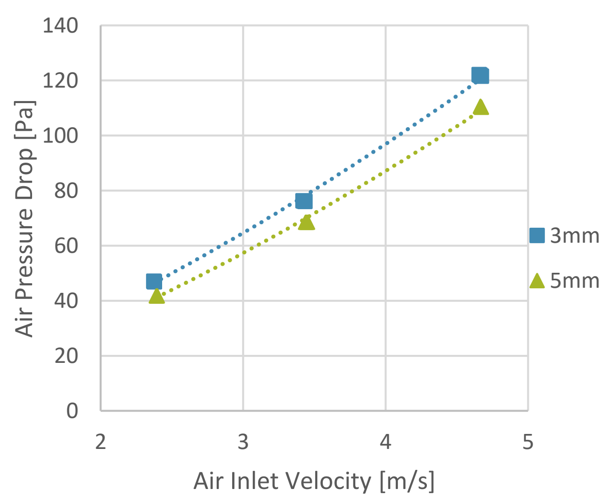


Figure 3: Dry air-side heat transfer and pressure drop results from hot water tests: Coils *OD3 – New* and *OD5 – New*

Figure 4 shows the difference in capacity between the new 3mm and 5mm samples, the 3mm design averages a 12% higher heat load than the 5mm prototype. These results again confirm the potential value of 3mm OD designs over larger diameter options: these designs can provide better thermal-hydraulic performance with dramatically reduced material consumption, size, and refrigerant charge.

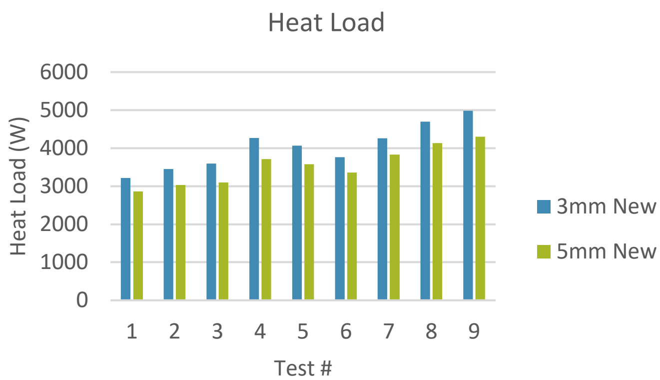


Figure 4: Heat load comparison from hot water tests

3.2 Cold Glycol (Wet-Condition) Testing

New tests were performed on the prototype heat exchangers using a cold mixture of propylene glycol (32% by weight) and water as the working fluid in dehumidifying wet conditions. The purpose of these tests is to study the impact that condensate has on heat transfer and pressure drop performance for the new 3mm HXs relative to 5mm ones. Heat exchangers employing smaller diameter tubes typically employ smaller longitudinal tube pitches and make up for this reduced fin surface area with more fins (tighter fin spacing); this has the potential to make the 3mm designs more sensitive to the detrimental effects of condensate retention because the gap between fins is already smaller than their 5mm counterparts. Table 3 summarizes the test matrix for wet condition testing and results in broad coverage of air velocities and sensible heat ratios. Figure 5 shows a comparison of dry vs wet pressure drop, along with the percent difference between the two for each prototype coil. As expected, the presence of condensate in wet conditions increases the air pressure drop of all samples. In the 1.5-3m/s velocity range of interest, coils in wet conditions had 100~200% higher pressure drops than they experienced in dry conditions. One concern with small diameter coils is that their fin densities tend to be higher and can become more sensitive to retained condensate. However, when comparing the center and right plots, it is clear that the wet condition air pressure drop of OD3 and OD5 are quite similar. This result indicates that a well-designed 3mm HX can achieve capacities and air pressure drops competitive with 5mm equivalents, even in wet conditions.

Table 3: Cold Glycol Test Matrix
(for *OD3 – Original, OD5 – Original, RD3 – Original, RD3 – Coated, OD5 – Coated)*

Test Number	Air Inlet Temperature [°C]	Air Inlet RH [%]	Water Inlet Temperature [°C]	Air Velocity [m/s]	Water mass flow rate [g/s]
1	23.9	72	10.0	1.1	200
2	23.9	72	10.0	1.1	250
3	23.9	72	10.0	1.1	300
4	23.9	72	10.0	1.7	200
5	23.9	72	10.0	1.7	250
6	23.9	72	10.0	1.7	300
7	23.9	72	10.0	2.2	200
8	23.9	72	10.0	2.2	250
9	23.9	72	10.0	2.2	300
10	21.1	68	10.0	1.1	200
11	21.1	68	10.0	1.1	250
12	21.1	68	10.0	1.1	300
13	21.1	68	10.0	1.7	200
14	21.1	68	10.0	1.7	250
15	21.1	68	10.0	1.7	300
16	21.1	68	10.0	2.2	200
17	21.1	68	10.0	2.2	250
18	21.1	68	10.0	2.2	300

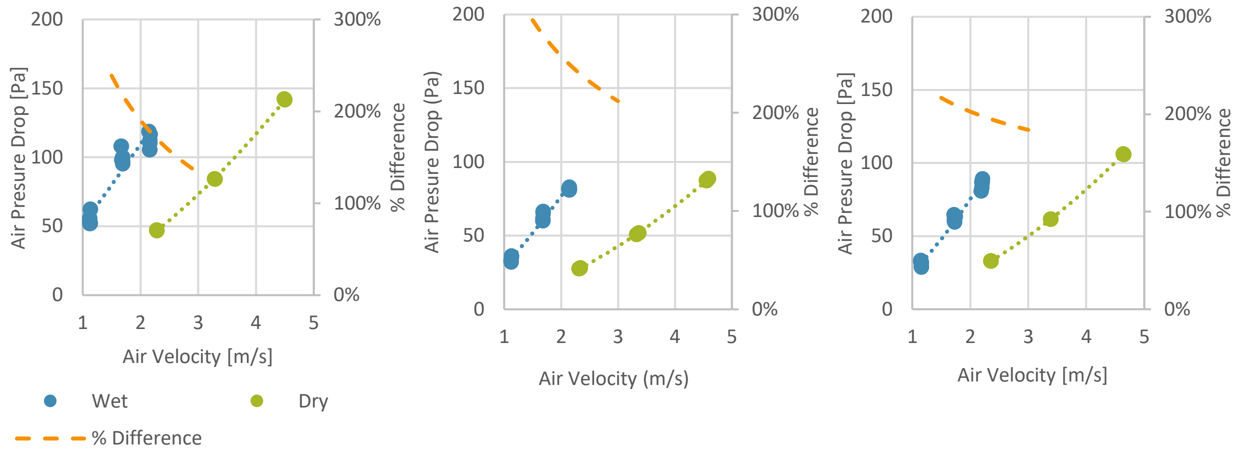


Figure 5: Air pressure drop in wet vs dry conditions for RD3 -Original (left), OD3 – Original (middle), OD5 – Original (right**)**

Although heat transfer and pressure drop correlations were developed only for dry conditions, they can be used for simulations in wet conditions to estimate performance. Figure 6 shows the simulated and measured heat load (and sensible heat load) for each wet test of each coil. The experimental results are reasonably well predicted by the simulations; deviations are greater than they are in dry conditions due to the unmodeled differences in wet condition convective heat transfer and the higher energy balance error in wet tests.

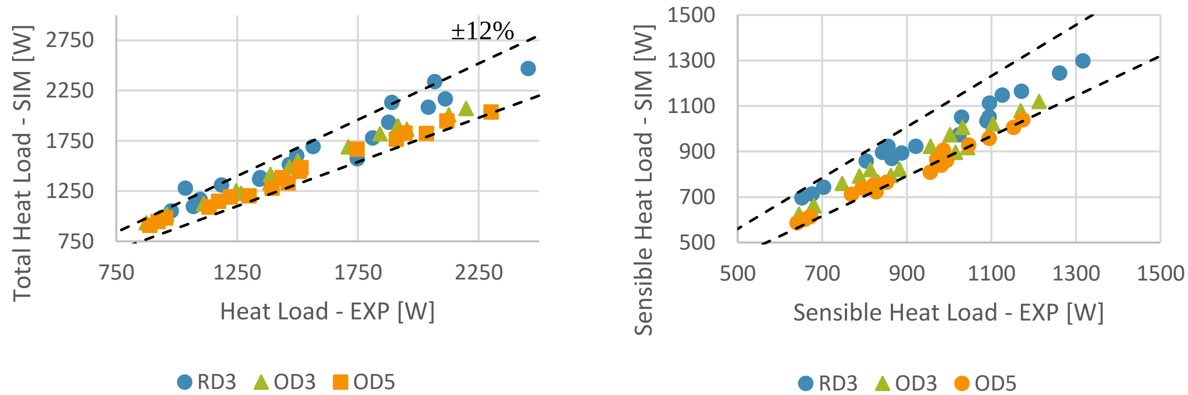


Figure 6: Simulated and experimental capacities in wet condition (12% error bars) for RD3-, OD3-, OD5 - Original

Additional copies of OD5 and RD3 were treated with a durable superhydrophobic coating and tested under the same conditions. Figure 7 shows the differences in performance: for the 5mm sample the difference is negligible, showing the coating neither adds flow resistance or aids in moisture shedding. The high fin density 3mm sample has higher air pressure drop when coated, which may indicate that an overly thick application of coating has reduced the flow area.

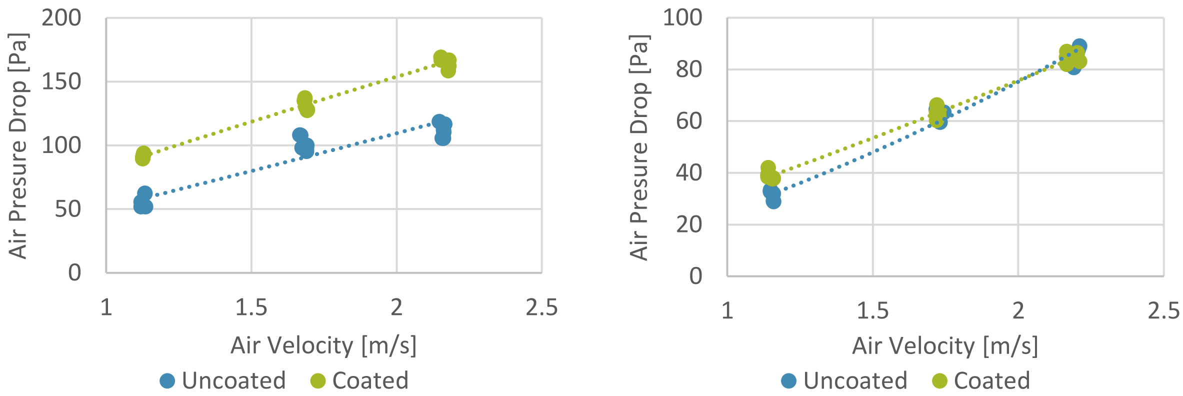


Figure 7: Air pressure drop in wet conditions for coated and uncoated coils
(left: *RD3 - Coated*, right: *OD5 - Coated*)

3.3 Frosting Condition Testing

A series of tests were conducted using chilled glycol as the working fluid at conditions below the freezing temperature of water. To emulate representative frosting conditions, the wind tunnel fan speed was fixed such that air flow rate would decrease with the accumulation of frost and increase in flow resistance. In an attempt to improve consistency between tests, all tests were initiated with dry coils. Table 4 summarizes the test conditions conducted for 3 and 5mm samples. The assignment of operating conditions for frost testing requires compromises: while in typical performance tests it is desirable to test two heat exchangers being compared under identical flow conditions, when comparing HXs in frosting that have different capacities, it is sometimes also important to test under different operating conditions but with the same capacity to observe differences in frost growth under the same load. As such, a range of conditions were evaluated to allow for these types of comparisons of frosting behavior between 3mm and 5mm samples as well as coated vs uncoated samples. Two HX sample designs were tested in frost conditions: OD5 and RD3, as well as coated copies of each.

Table 4: Frost Condition Test Matrix

Test No.	**Air Velocity**	**DB Temp. Actual**	**RH**	**Glycol Inlet Temperature**	**Air Velocity**	**DB Temp. Actual**	**RH**	**Glycol Inlet Temperature**
	m/s	°C	%	°C	m/s	°C	%	°C
	5mm coils				3mm coils			
1	1.1	8.3	72	-3.6	1.1	8.3	72	-3.5
2	1.1	1.7	88	-3.3	1.1	1.7	90	-2.4
3	1.7	1.7	96	-3.3	1.7	1.7	94	-2.5
4	1.1	0.0	92	-3.3	1.1	0.0	90	-2.5
5	1.7	0.0	94	-3.3	1.7	0.0	92	-2.5
8	1.1	-1.1	91	-3.7	1.1	-1.1	88	-4.0
9	1.1	-1.1	94	-3.7	1.1	-1.1	92	-3.0

*Test 6 and 7 are omitted here due to challenges with test condition stability

Several notable insights were gained through this comparative testing in frost conditions:

1. Under comparable conditions, this 3mm coil developed restrictive frost significantly faster than its 5mm counterpart. This is in large part due to the smaller gap between fins, about 38% less time in the 26.8 FPI 3mm coil than the 17.4 FPI 5mm HX. With a tighter fin density, the same thickness of frost blocks a greater fraction of the air free flow area and results in a more rapid increase in pressure drop. Figure 8 shows a comparison between several repeat tests of 3 and 5mm coils under comparable conditions. Note that because the 3mm coil has greater thermal performance than the 5mm one, this test is performed with a slightly reduced ΔT between fluids such that they achieve comparable capacity. Comparing these results, it is clear that the 5mm coil can continue operating for about 150% more time than the 3mm one before reaching the same

highly frosted state.

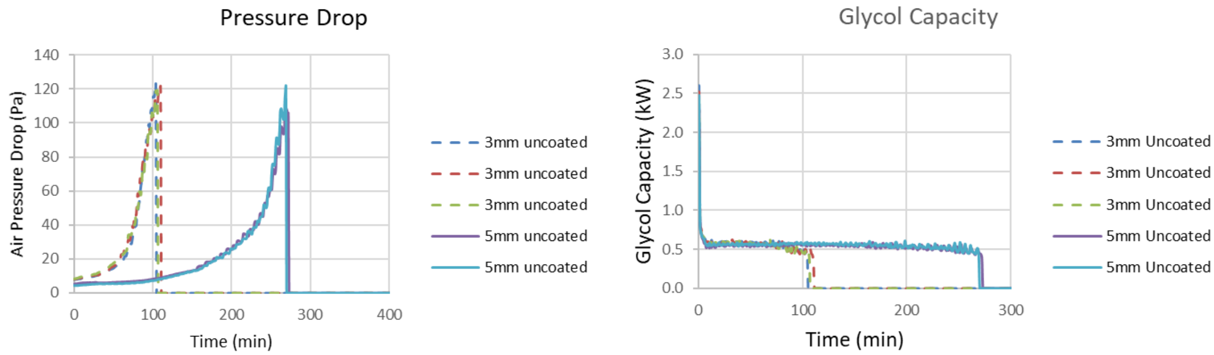


Figure 8: Test #8 comparison between 3 and 5mm HXs

2. <u>Coatings show evidence of frost inhibition.</u> Figure 9 shows comparisons between uncoated and coated samples in the same test conditions. It is evident that for both the 3 and 5mm coils, the coated sample is able to operate more than 100% longer than the uncoated one before reaching the same level of blockage. It is important to note, however, that significant variability exists between different operating conditions and even within test points with the same operating conditions. In other words, the difference between coated and uncoated coils becomes less clear in certain operating conditions, including some where uncoated coils outperformed coated ones.

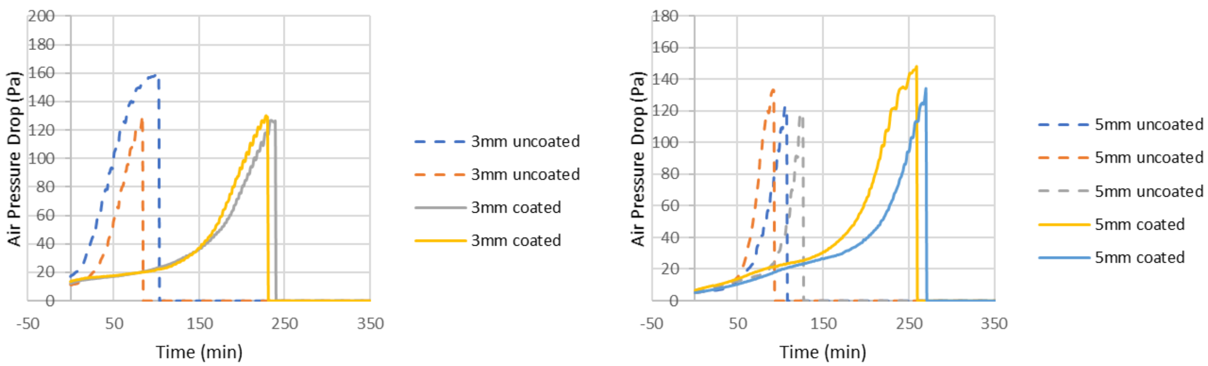


Figure 9: Example comparisons between uncoated and coated samples in test #4 conditions (3mm left, 5mm right)

3. <u>Repeatability and consistency issues are prevalent in frosting tests.</u> The analysis of results collected in this effort revealed enormous variations in performance despite tight control of environmental conditions. All tests were repeated 2-3 times and the outcomes often varied considerably: for 3mm tests the average standard deviation in frosting duration for repeat tests was around 22%. Figure 10 shows one such example where the same coil was retested three times on different days under conditions identical (within the control capabilities of the facility) yet reached peak frost in times that varied by as much as 96%. This particular "plateau" behavior is only seen in a subset of tests but reveals an unstable behavior where near-identical initial conditions can produce vastly different outcomes as a result of minute variations in operating conditions. There is some evidence that this behavior occurs primarily in the first frost cycle and thus can be avoided through conducting cyclic frost tests. In cyclic tests, the coil is never fully dried after a defrost cycle is completed. However, the limited cyclic tests performed as part of this work still exhibited significant variation between cycles. This is an important consideration for future testing.

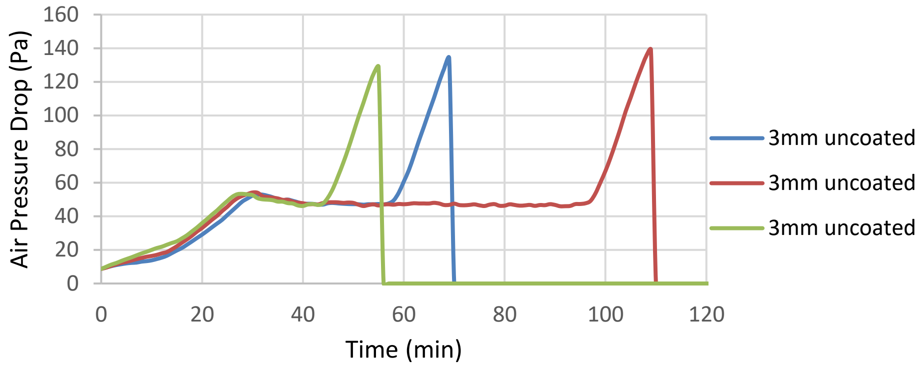


Figure 10: Repeat tests of condition 1

4. CONCLUSIONS

This research is presented in support of continued incremental progress in conventional tube-fin heat exchanger design. Just as 5mm OD tube-fin HXs came to prominence in recent years due to their superior compactness and material savings, 3mm OD designs can also offer further improvements because the principle of increasing surface area with decreasing diameter remains valid.

- The new 3mm prototype HX has 31% less mass, 47% less internal volume, and 30% less envelope volume than the 5mm design while achieving a 12% higher capacity and 10% higher air pressure drop. This represents significant potential for cost savings, miniaturization, and refrigerant charge reduction relative to the current state of the art tube-fin design.
- In wet conditions, all heat exchangers experience higher airside pressure drops than in dry conditions at the same velocity. Higher fin density continues to lead to higher air pressure drops, but the 3mm coils are not penalized significantly more than 5mm ones. The results indicate that 3mm HXs can be viable as evaporators in dehumidifying conditions to the same extent that 5mm designs can.
- In frost-forming conditions, the 3mm sample reached a high level of air flow restriction which would require defrosting must more rapidly than its 5mm counterpart under comparable conditions. This results from the higher fin density of the 3mm design which has 38% less free flow area and is more sensitive to frost accumulation between fins. A 3mm design with wider fin spacing might accumulate frost at a more comparable rate to the 5mm one, but it is important to consider that higher fin density is a typical design attribute of small diameter HXs that usually have less depth in the airflow direction.
- Precise quantitative conclusions about performance in frosting conditions remain elusive. There is some evidence that surface coatings can inhibit the growth of frost or accelerate its shedding, but significant variability exists in these tests and further research is necessary. Only one coating was investigated in this effort, but a growing body of research is evaluating the potential of a wide range of coatings and surface treatments

The improvements offered by 3mm HXs do come with the potential for significant implementation challenges: the assembly and brazing of these HXs will inevitably be more challenging than larger diameter options and care must be taken in designing for wet and frost-forming conditions. However, 3mm tube-fin heat exchangers do provide an attractive opportunity for substantially greater miniaturization and optimization of air to refrigerant heat exchangers in applications where these challenges can be overcome.

NOMENCLATURE

A	Area	(m^2)
DB	Dry Bulb Temperature	(°C)
FPI	Fins per Inch	(in^{-1})
h, HTC	Heat transfer coefficient	(W/m^2K)
LMTD	Log mean temperature difference	(K)
OD	Outer Diameter	(mm)
R	Thermal resistance	(K/W)
RH	Relative Humidity	(%)
U	Overall heat transfer coefficient	(W/m^2K)
η_0	Fin effectiveness	(-)

REFERENCES

Bacellar, D., Aute, V., Huang, Z., & Radermacher, R. (2016). Airside friction and heat transfer characteristics for staggered tube bundle in crossflow configuration with diameters from 0.5 mm to 2.0 mm. *International Journal of Heat and Mass Transfer*, *98*, 448–454. https://doi.org/10.1016/j.ijheatmasstransfer.2016.02.072

Bacellar, D., Aute, V., & Radermacher, R. (2014). *CFD-Based Correlation Development For Air Side Performance Of Finned And Finless Tube Heat Exchangers With Small Diameter Tubes*. International Refrigeration and Air Conditioning Conference, Purdue University. http://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=2409&context=iracc

Bacellar, D., Aute, V., & Radermacher, R. (2016, July 11). *CFD-Based Correlation Development for Air Side Performance of Wavy Fin Tube Heat Exchangers using Small Diameter Tubes*. 16th International Refrigeration and Air Conditioning Conference at Purdue. http://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=2612&context=iracc

Bacellar, D., Nasuta, D., Li, S., Martin, C., & Powell, D. (2021). *Design Optimization of 3mm and 5mm Copper Tube and Flat Fin Air-to-Water Heat Exchangers with Experimental Validation*. 9.

Gnielinski, V. (1976). New Equations for Heat and Mass Transfer in Turbulent Pipe and Channel Flow. *International Chemical Engineering*, *16*(2), 359–368.

Nasuta, D., Li, S., Hwang, Y., & Martin, C. (2018). *Experimental Validation of CFD-Based Correlations for 5 mm Louver- and Slit-Fin Heat Exchangers: Lessons Learned*. 11.

Radermacher, R., Bacellar, D., Aute, V., Huang, Z., Hwang, Y., Ling, J., Muehlbauer, J., Tancabel, J., Abdelaziz, O., Zhang, M., Oak Ridge National Lab. (ORNL), Oak Ridge, TN (United States), Luvata Inc., International Copper Association, Heat Transfer Technologies LLC., Wieland, & Burr Oak Tool. (2017). *Miniaturized Air-to-Refrigerant Heat Exchangers* (DOE-UMD-EE--00006114, 1358252; p. DOE-UMD-EE--00006114, 1358252). https://doi.org/10.2172/1358252

Sarpotdar, S., Nasuta, D., & Aute, V. (2016a). CFD Based Comparison of Slit Fin and Louver Fin Performance for Small Diameter (3mm to 5 mm) Heat Exchangers. *16th International Refrigeration and Air Conditioning Conference at Purdue, July 11-14, 2016*.

Sarpotdar, S., Nasuta, D., & Aute, V. (2016b). CFD-Based Airside Heat Transfer and Pressure Drop Correlation Development for Small Diameter (3 mm to 5 mm) Louver Fin Heat Exchangers. *16th International Refrigeration and Air Conditioning Conference at Purdue, July 11-14, 2016*.

ACKNOWLEDGEMENT

This work was supported by the Copper Development Association, Inc. The authors would also like to acknowledge Burr OAK Tool for providing the manufacturing means and building the small diameter tube prototypes.