3-5 mm Microgroove Heat Exchangers in Frost-Developing Conditions

December 7th, 2021

Dennis Nasuta, Song Li, Regina Hong

7040 Virginia Manor Road, Beltsville MD 20705 | Tel: +1 866-485-8233 | www.optimizedthermalsystems.com

Who are we?

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Serving the HVAC&R industry through cutting edge research, state-of-the-art software, and performance measurements and verification new technologies that can reduce energy consumption and address growing environmental concerns.

Cu Copper Development Association Inc.

Defend and grow markets for copper based on its superior technical performance and its contribution to a higher quality of life worldwide. Members include copper mining and fabricating companies

Contributors:

Dennis Nasuta

- M.S., Mechanical Engineering
- *University of Maryland*
- Joined OTS in 2011
- Contact Info: nasuta@optimizedthermalsystems.com

Song Li

- M.S., Mechanical Engineering
- *University of Maryland*
- Joined OTS in 2014
- Contact Info: li@optimizedthermalsystems.com

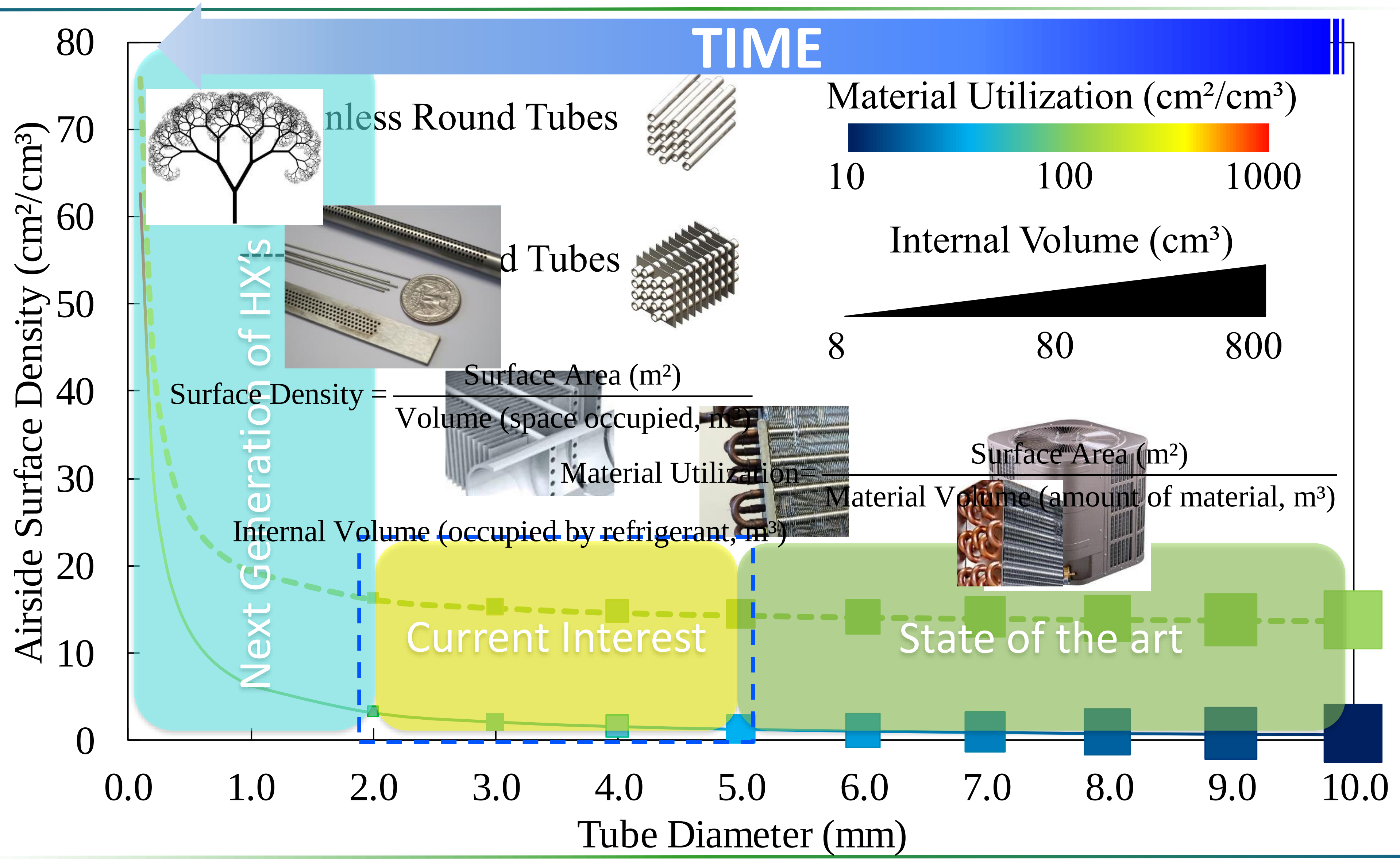
Regina Hong

- B.S., Mechanical Engineering
- *University of Maryland*
- Joined OTS energy in 2021
- Contact Info:
- regina.hong@otsenergy.com

Contents

- Past work
  - 3mm and 5mm tube fin heat exchangers
  - Performance testing and model validation
- Impacts of frost
- Frost testing approach
- Selected results
  - 3mm vs 5mm
  - Effect of coatings
  - Repeatability and cyclic performance
- Conclusions / discussion

Why Small Diameter Tubes?



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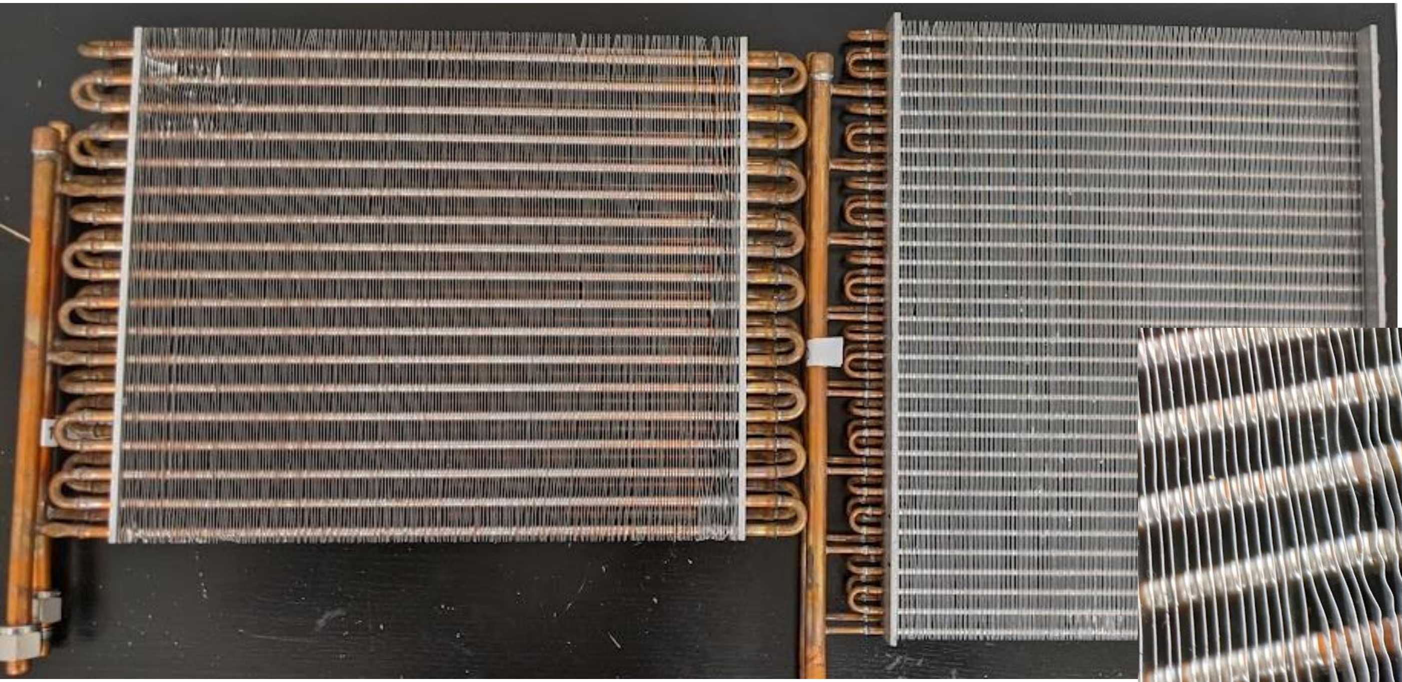
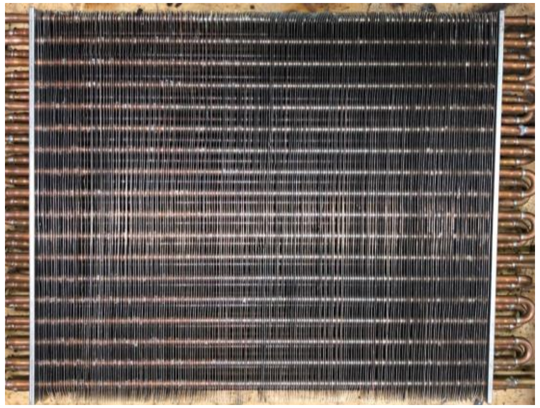
3mm OD Heat Exchangers

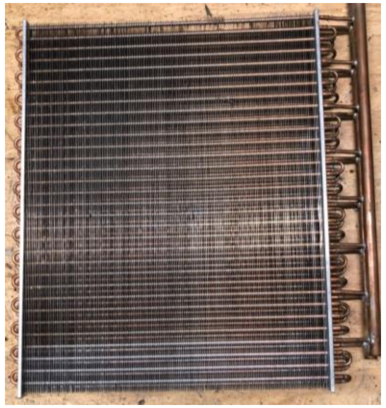


Test Coils (Purdue Paper Recap)

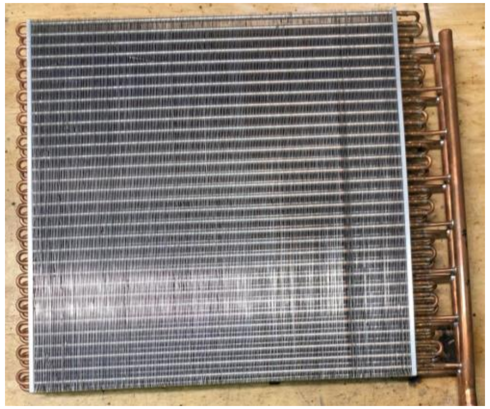
5mm Baseline



Comparable Performance



Comparable Surface Area



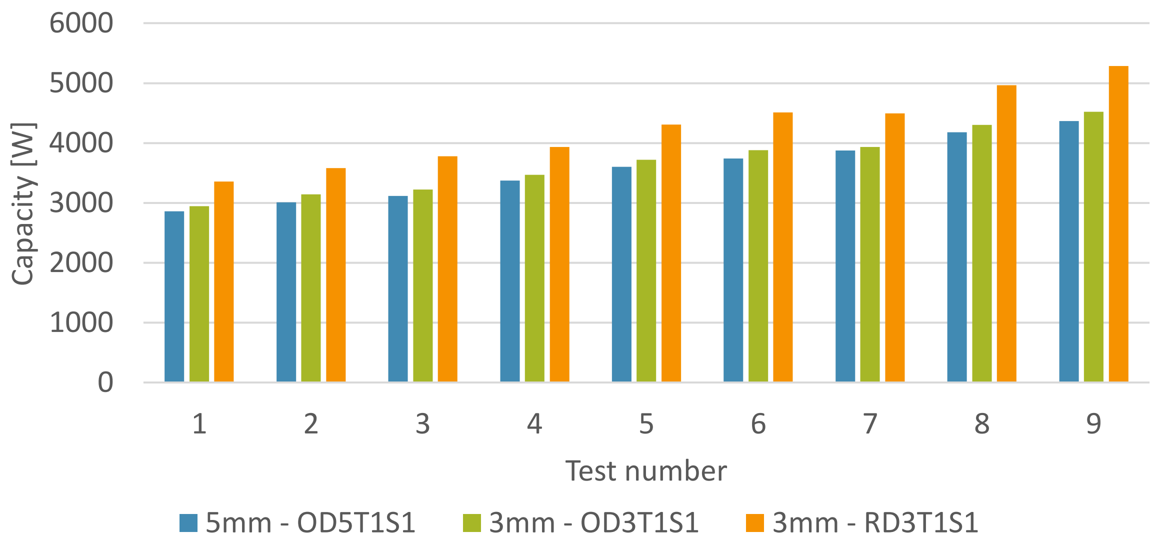
Coil		5mm coil – Design (Actual)	3mm coil 1– Design (Actual)	3mm coil 2– Design (Actual)
D_o	m	0.005 (0.005)	0.003 (0.003)	0.003 (0.003)
FPI	in^{-1}	17.2 (18.7) ↑8.2%	23.9 (20.8) ↓12.9%	28 (28.3) ↑0.3%
A_o	m^2	1.837 (1.971) ↑7.3%	1.823 (1.575) ↓13.6%	1.858 (1.865) ↑0.3%

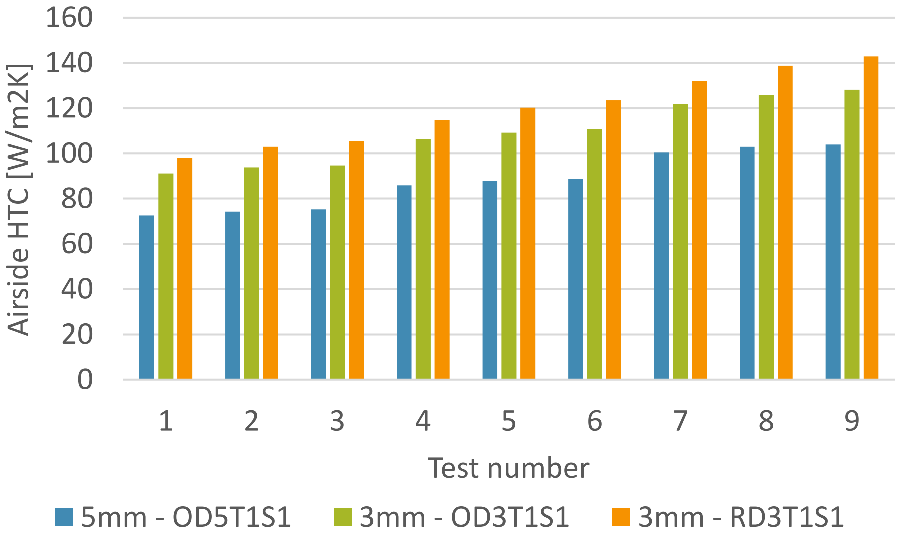
- Flat/plate fins
- Coils designed for equivalent performance: similar face and heat transfer area
- Actual coils fabricated differently from design specifications
- Frost tested coils: similar face area and surface area – 3mm has higher capacity and pressure drop!

D. Bacellar et al., "Design Optimization of 3mm and 5mm Copper Tube and Flat Fin Air-to-Water Heat Exchangers with Experimental Validation" presented to International Refrigeration and Air Conditioning Conference at Purdue, May 24-28, 2021.

3mm vs. 5mm Coils (Dry Tests)

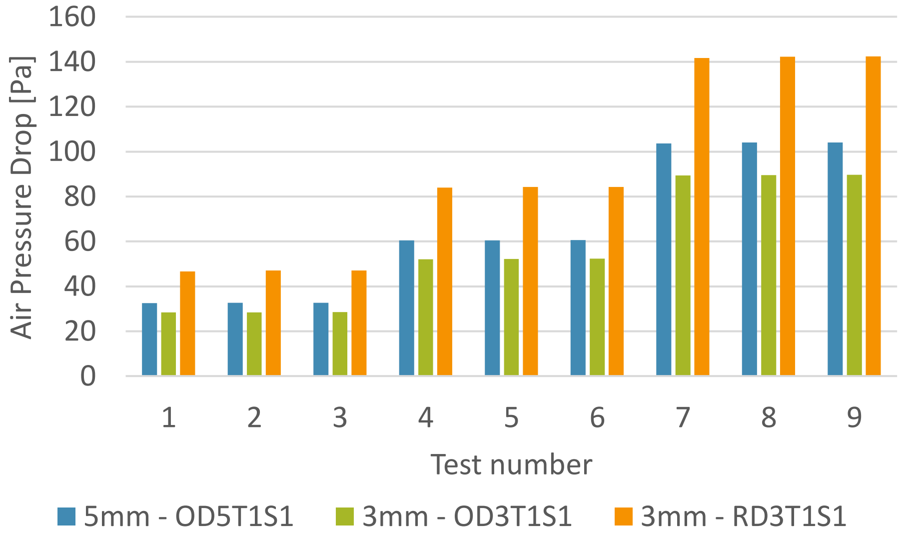
3mm OD designs achieve ***higher capacity*** *than* ***5mm*** *at the same test conditions:*





OD3 *has* ***better capacity, HTC, and lower ΔP*** *than* ***OD5***

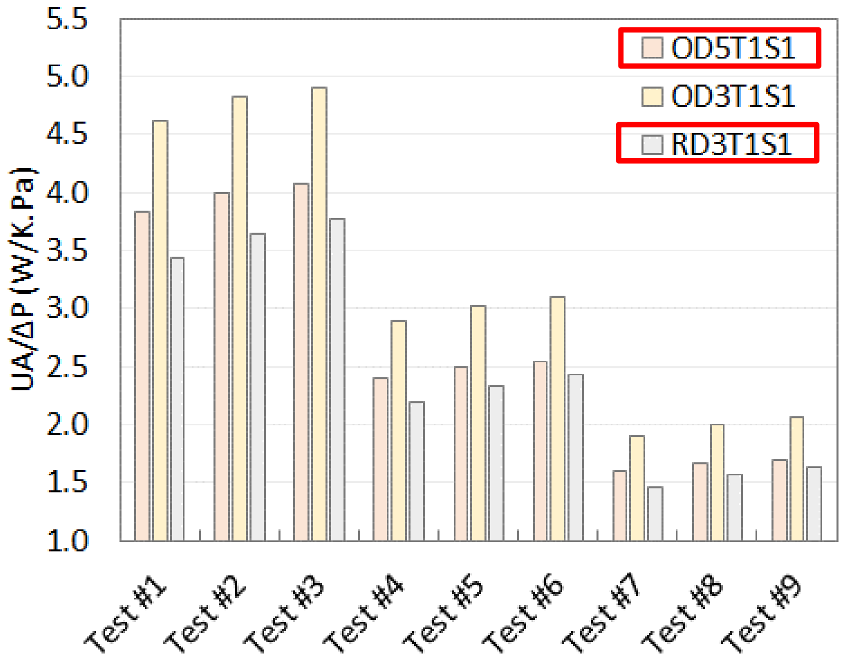
RD3 *has the* ***highest capacity and HTC, but also has the highest air ΔP*** *– this is the 3mm coil* *<u>used in subsequent tests</u>*



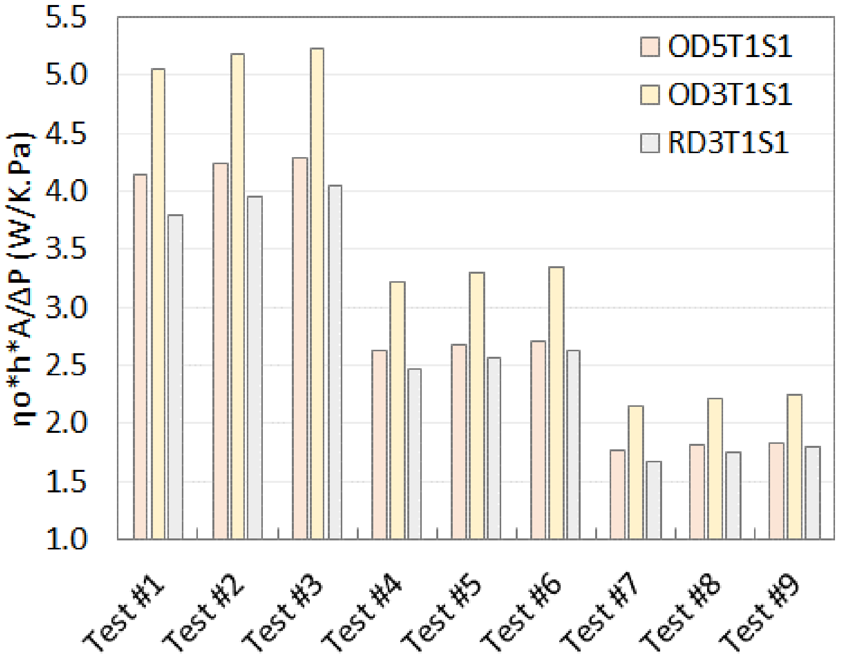
Thermal-Hydraulic Characteristics

$$ratio: \frac{heat\ transfer\ performance}{pressure\ drop}$$

Total HX UA



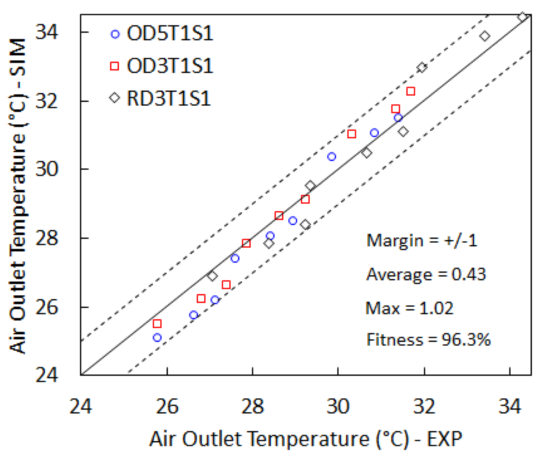
Effective *Air-side* heat transfer

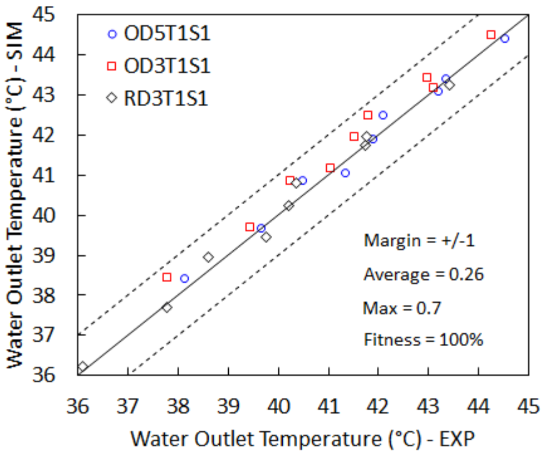


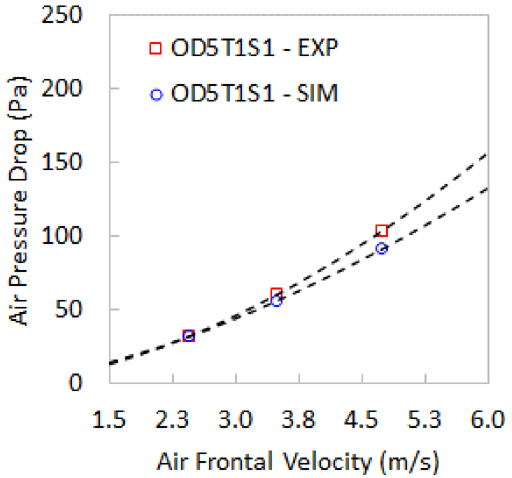
RD3T1S1 used for this frost testing is suboptimal – Better designs exist

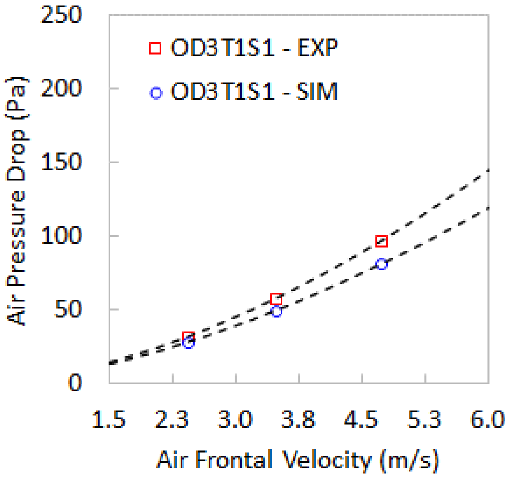
Model Validation

5mm: vs. 3mm:

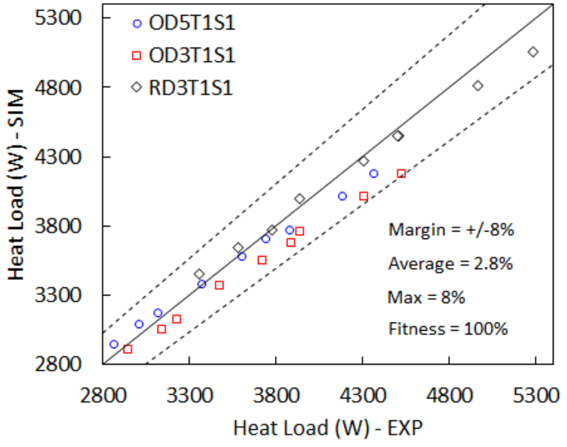


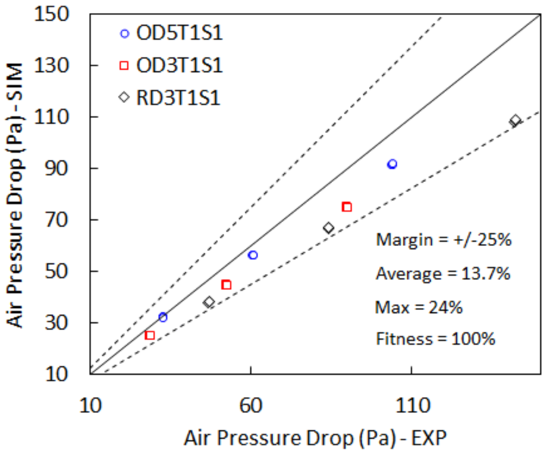


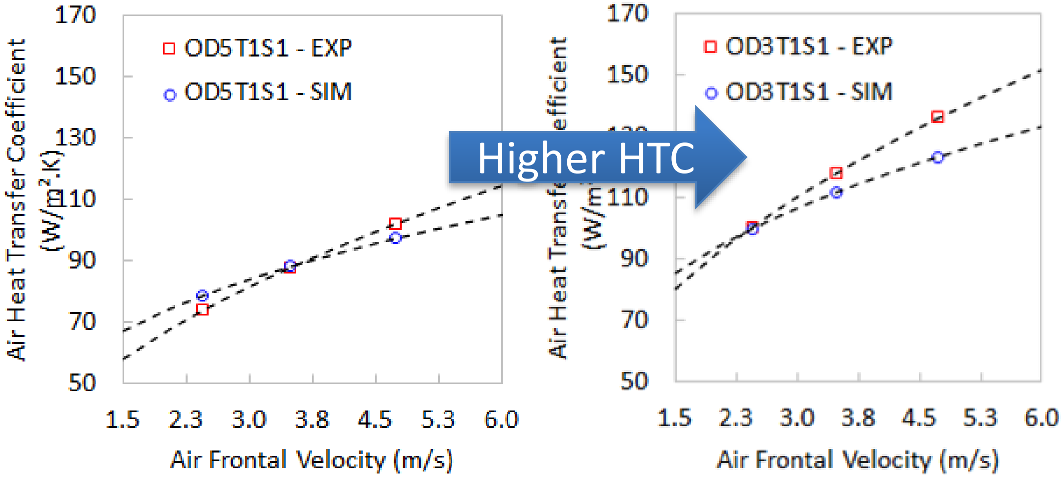




Excellent agreement with model predictions







Frost Conditions: Defrosting Energy Impacts

- Frost accumulation increases thermal resistance and restricts airflow, degrading capacity during runtime, but also:
- Frost must be cleared periodically, consuming additional energy that doesn't result in useful heat transfer to the conditioned space
- What is the value of changing frost/defrost time on this penalty?

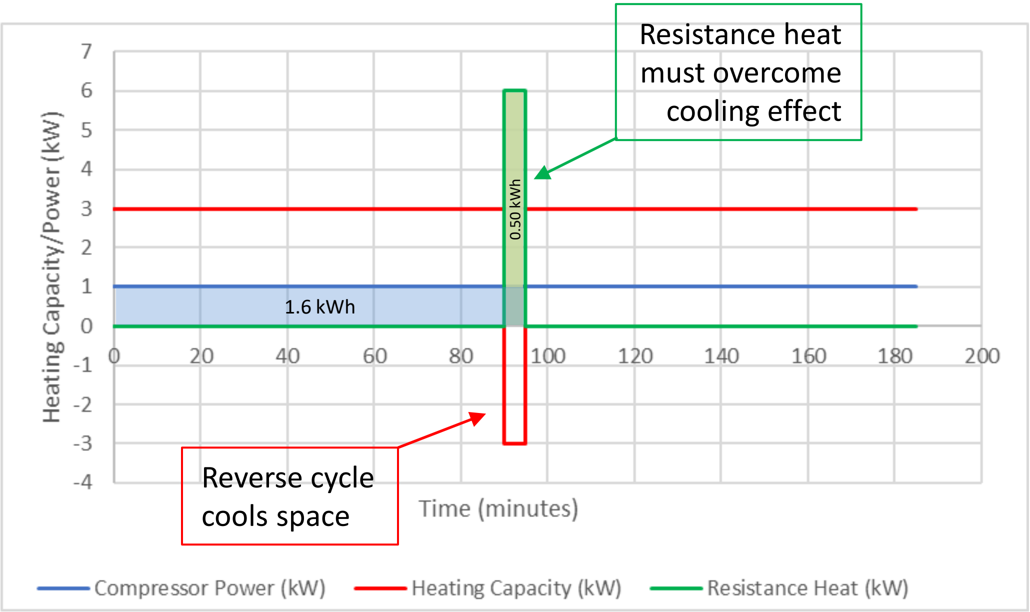
Defrosting Energy Impacts (cont.)

- **Frost Time: 90 minutes**
- **Defrost Time: 5 minutes**
- **COP: 3**

	No Defrost	Defrost – fan on	Defrost – fan off
Electricity In (kWh)	1.58	2.08	1.58
Heat Delivered (kWh)	4.75	4.75	4.5
Effective COP	3	2.28	2.85

24% lower effective COP

5% lower effective COP



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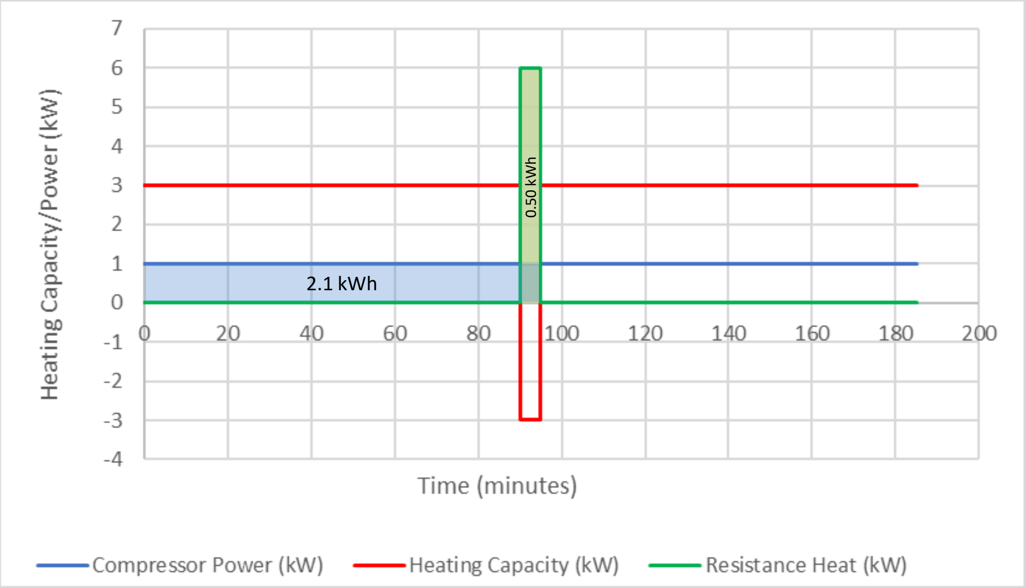
Defrosting Energy Impacts (cont.)

- **Frost Time: 120 minutes**
- **Defrost Time: 5 minutes**
- **COP: 3**

	No Defrost	Defrost – fan on	Defrost – fan off
Electricity In (kWh)	2.08	2.58	2.08
Heat Delivered (kWh)	6.25	6.25	6
Effective COP	3	2.42	2.88

19% lower effective COP

4% lower effective COP



If a coating can extend the runtime from 90 to 120 minutes, it may result in ~20% decrease in defrost penalty and 1-6% increase in effective COP

Effective COP- Frost Mitigation vs Cycle Improvement

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With fan on during defrost:

			COP Improvement					
Heating Interval (mins)	Defrost Interval (mins)	Defrost "ratio"	0%	2.00%	4.00%	6.00%	8.00%	10.00%
60	5	**0.0833**	2.06	2.10	2.13	2.16	2.19	2.23
90	5	**0.0556**	2.32	2.36	2.40	**2.44**	**2.48**	2.52
120	5	**0.0417**	**2.46**	2.51	2.55	2.60	2.64	2.68
150	5	**0.0333**	2.56	2.61	2.65	2.70	2.74	2.79
180	5	**0.0278**	2.63	2.67	2.72	2.77	2.82	2.87
210	5	**0.0238**	2.67	2.72	2.77	2.82	2.87	2.92

Extending heating interval from 90 to 120 mins is as good as improving base COP by 7%!

Fan off during defrost:

			COP Improvement					
Heating Interval (mins)	Defrost Interval (mins)	Defrost "ratio"	0%	2.00%	4.00%	6.00%	8.00%	10.00%
60	5	**0.0833**	2.77	2.82	2.88	2.94	2.99	3.05
90	5	**0.0556**	2.84	**2.90**	2.96	3.01	3.07	3.13
120	5	**0.0417**	2.88	2.94	3.00	3.05	3.11	3.17
150	5	**0.0333**	**2.90**	2.96	3.02	3.08	3.14	3.19
180	5	**0.0278**	2.92	2.98	3.04	3.09	3.15	3.21
210	5	**0.0238**	2.93	2.99	3.05	3.11	3.16	3.22

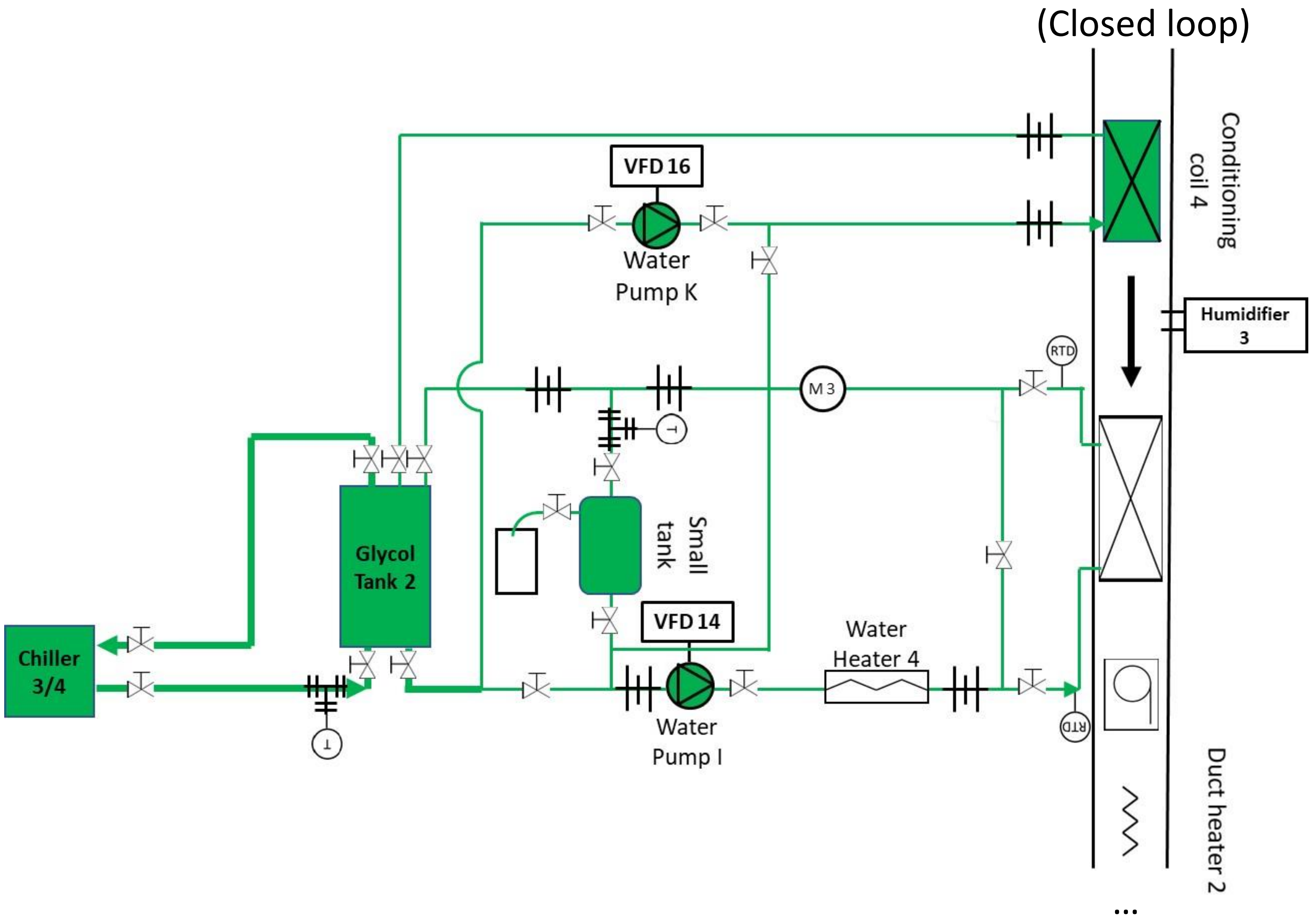
Extending heating interval from 90 to 150 mins is as good as improving base COP by 2%

Frost Testing

- Frost accumulation is a critical concern for heat pumps. Small diameter tube HXs often have smaller fin spacing → more sensitive to frost than larger-diameter counterparts
- Past work suggests that coatings may delay or help shed frost growth in some conditions
  - Superhydrophobic coatings may reduce condensate retention before frost growth and/or accelerate frost or water shedding during defrosting
- Coated coils tested with NEI's NANOMYTE® SuperCN which is highly hydrophobic and designed specifically for metal substrate
- 4 Testing Configurations:
  - 3mm uncoated
  - 3mm coated
  - 5mm uncoated
  - 5mm coated

Coil #	Surface Area	Envelope Volume	Internal Volume	Material Mass	Fin Spacing
-	mm^2	mm^3	mm^3	kg	mm
3mm	1.85E06	8.97E05	8.56E04	0.572	0.79
5mm	1.83E06 (↓1.1%)	1.44E06 (↑61%)	1.45E05 (↑69%)	0.770 (↑35%)	1.36 (↑72%)

Test Schematic



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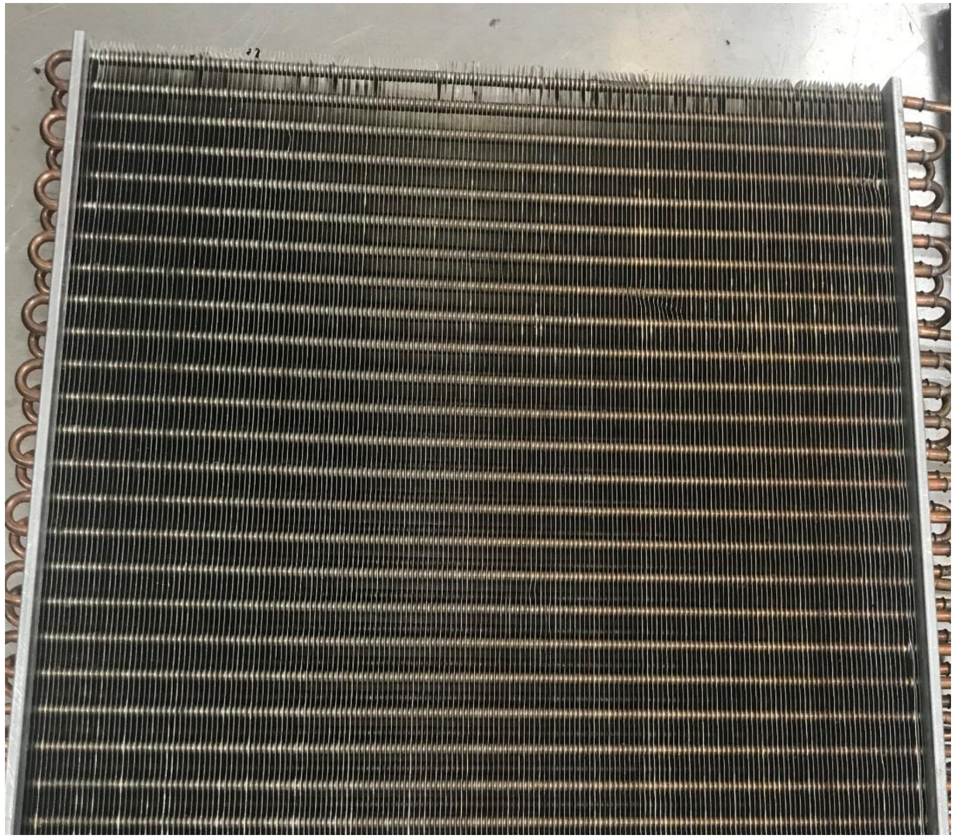
Test Conditions Matrix (5mm Coils)

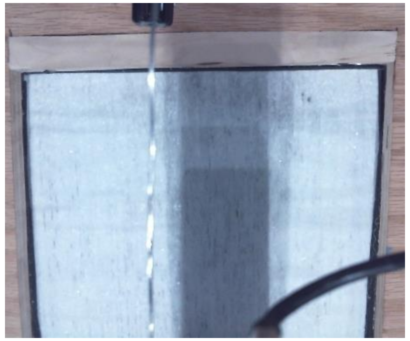
Test Condition		Coated	Air Velocity	DB Temp. Actual	RH	Glycol Flow Rate	Glycol Inlet Temperature
#			m/s	°C	%	g/s	C
Test #1	H1	No	1.1	8.33	72	300	-3.6
Test #2	H2		1.1	1.67	88		-3.25
Test #3	H2		1.65	1.67	95.5		-3.25
Test #4	A2		1.1	0.00	92		-3.3
Test #5	A2		1.65	0.00	94		-3.35
Test #8	B2		1.1	-1.11	90.5		-3.7
Test #9	B3		1.1	-1.11	93.5		-3.7

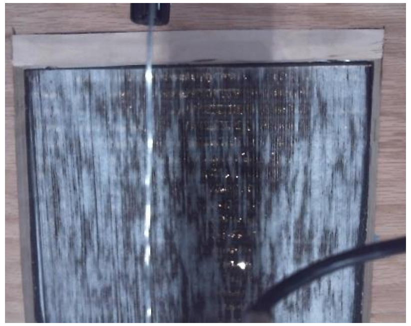
Test Conditions Matrix (3mm Coils)

Test Condition		Coated	Air Velocity	DB Temp. Actual	RH	Glycol Flow Rate	Glycol Inlet Temperature
#			m/s	°C	%	g/s	C
Test #1	H1	No	1.1	8.33	72	300	-3.45
Test #2	H2		1.1	1.67	90		-2.4
Test #3	H2		1.65	1.67	93.5		-2.5
Test #4	A2		1.1	0.00	89.5		-2.45
Test #5	A2		1.65	0.00	92		-2.45
Test #8	B2		1.1	-1.11	88		-4.00
Test #9	B3		1.1	-1.11	92		-3.00

3mm Coils

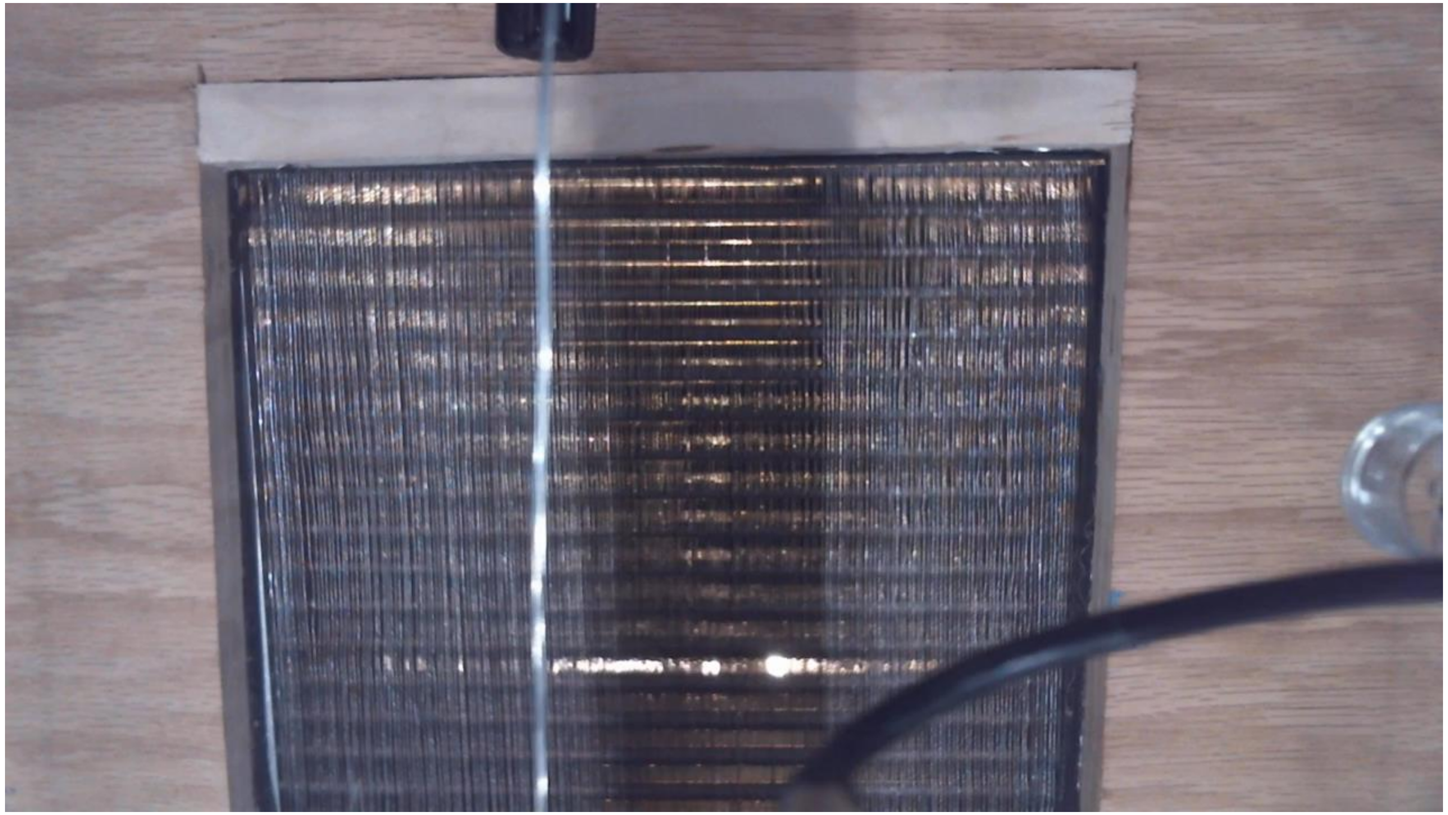




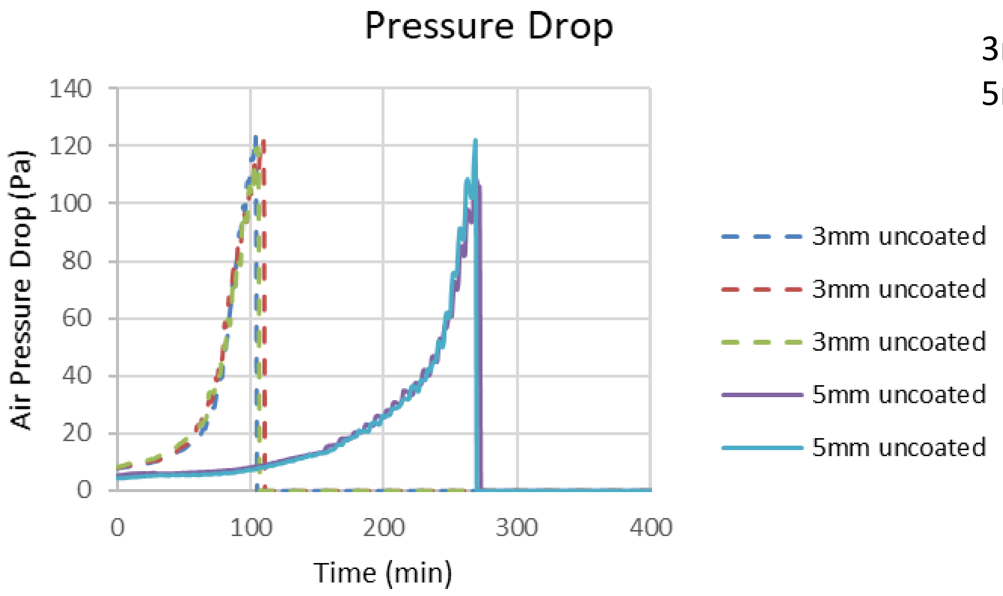


Sample Results

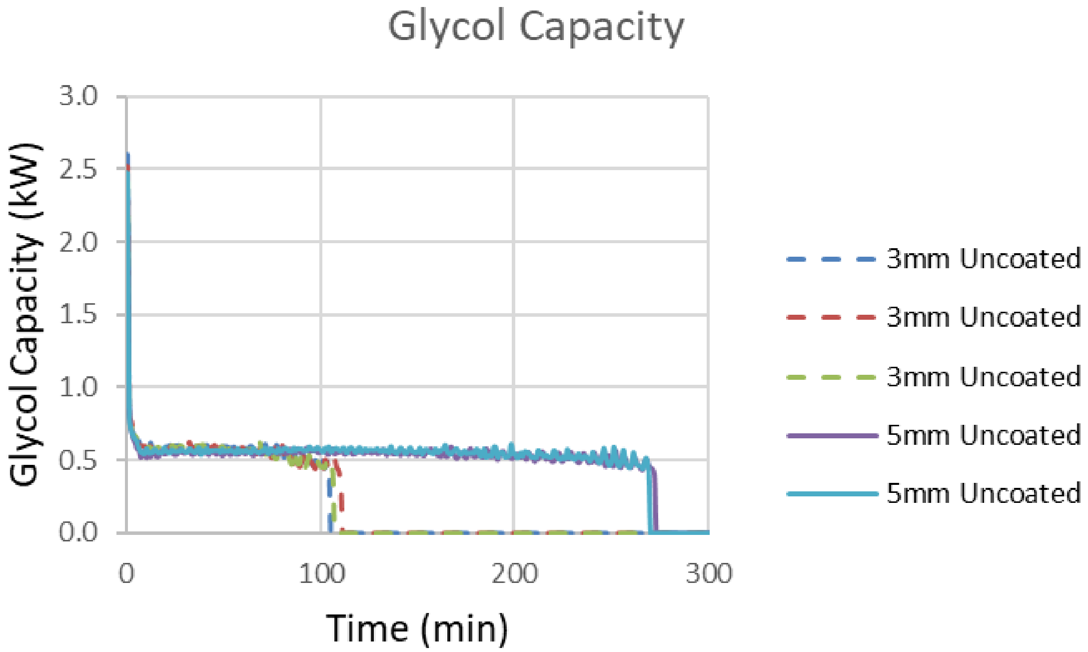
- **Frost Testing (300x speed):**



3mm v. 5mm Coils



3mm: A(-1.11C | 88% | 1.1 m/s) G(-4.00C | 300 g/s)
5mm: A(-1.11C | 90.5% | 1.1 m/s) G(-3.7C | 300g/s)



Under similar test conditions and glycol capacity, 5mm coils are frosting slower than 3mm coils

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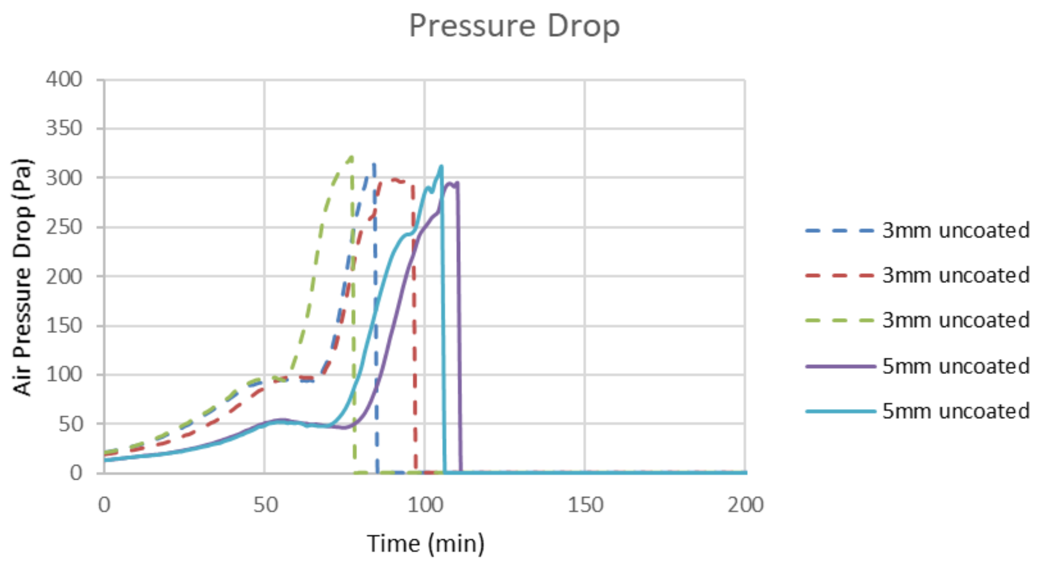
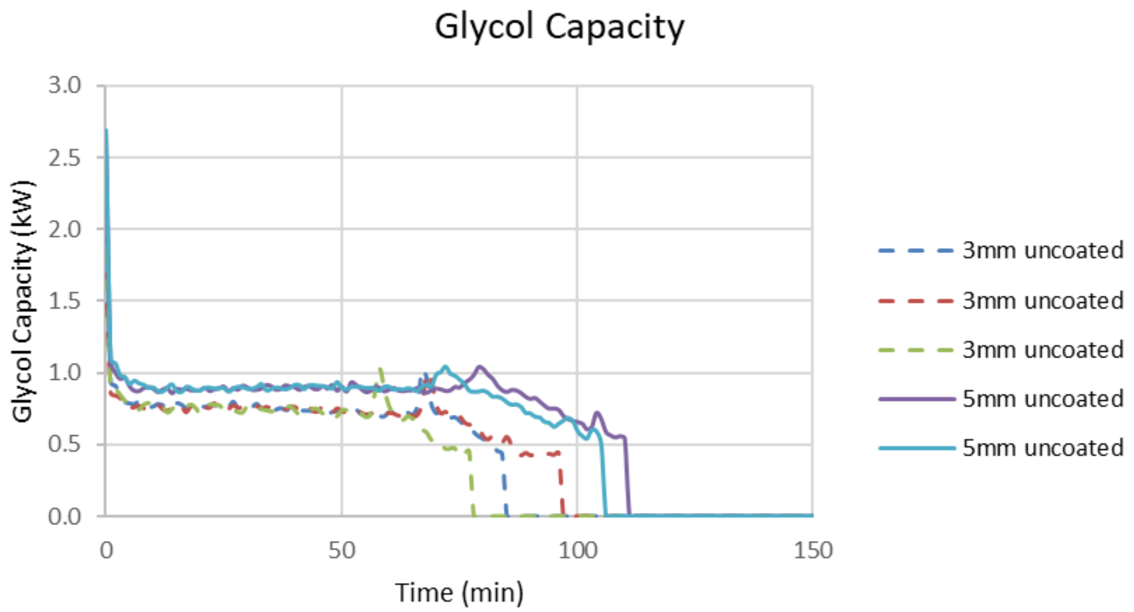
Sample Results (cont.)



3mm: A(1.67C | 93.5% | 1.65 m/s) G(-2.5C | 300 g/s)
5mm: A(1.67C | 95.5% | 1.65 m/s) G(-3.25C | 300g/s)

Even when 5mm is doing greater cooling load than 3mm, it still takes longer to frost



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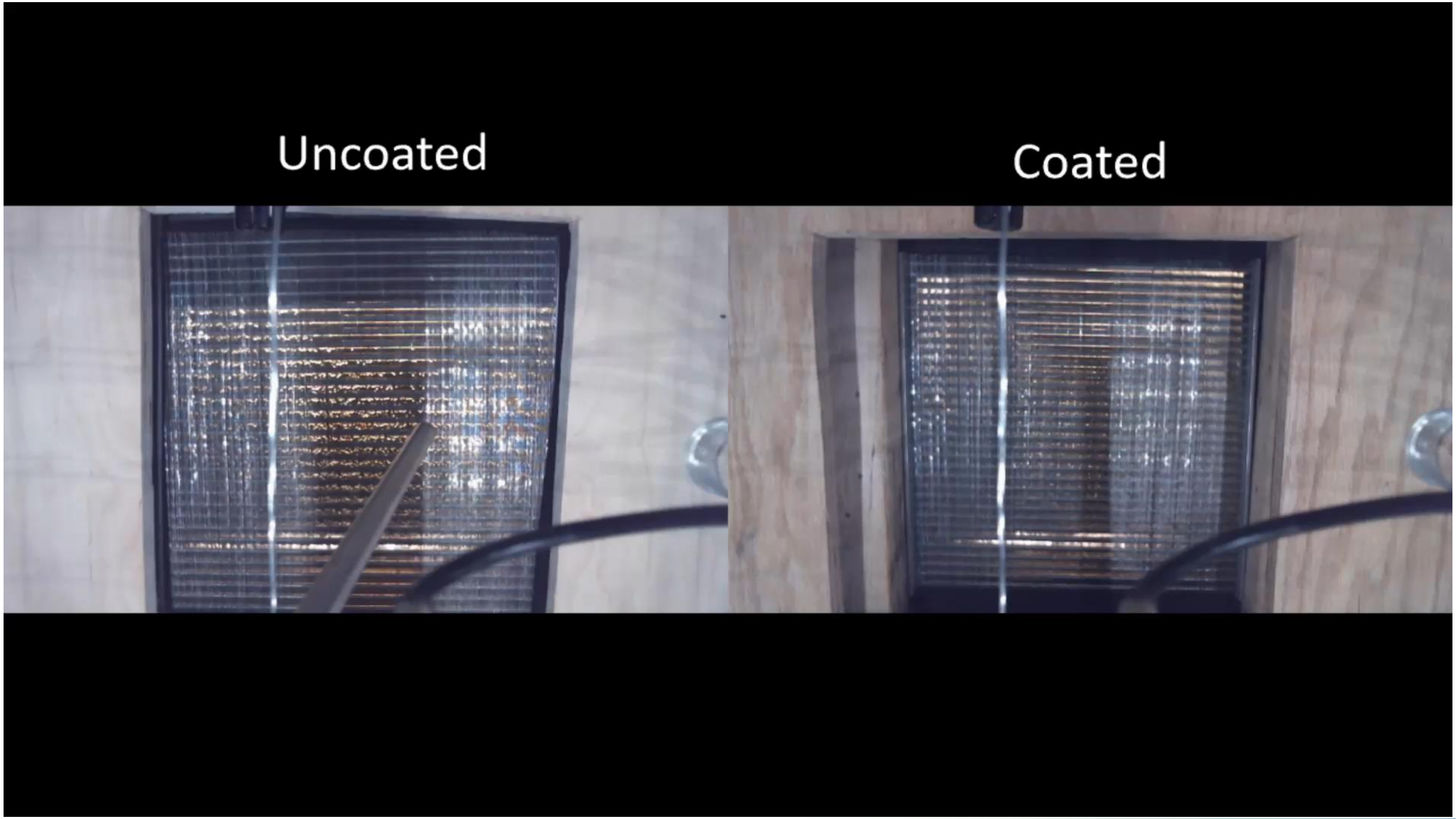
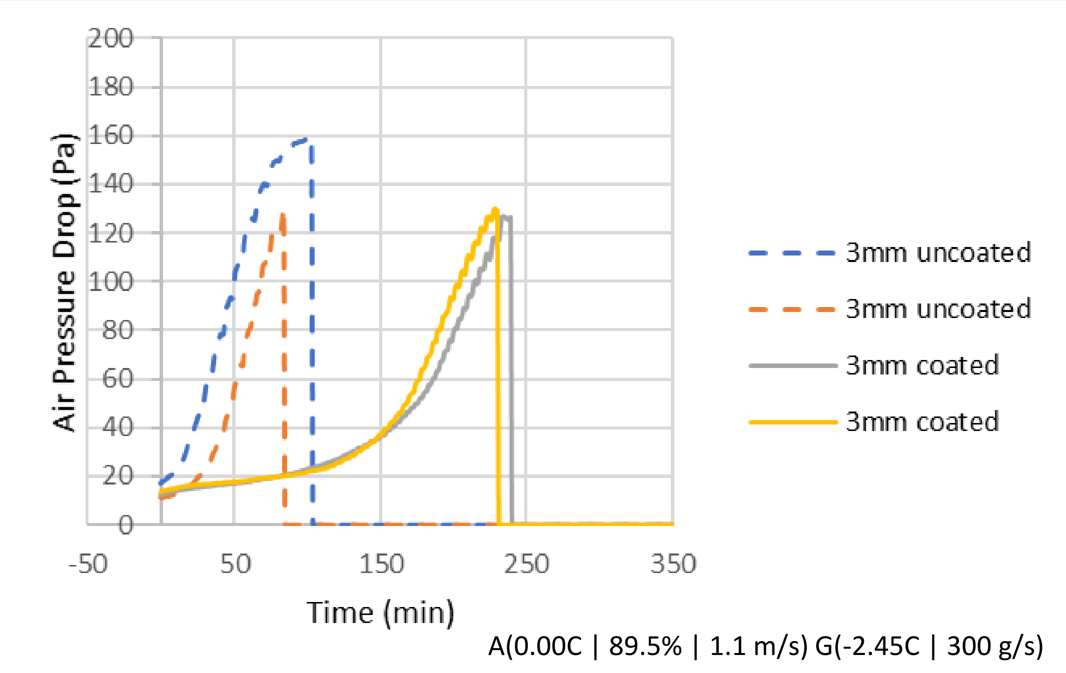
Effect of Coatings

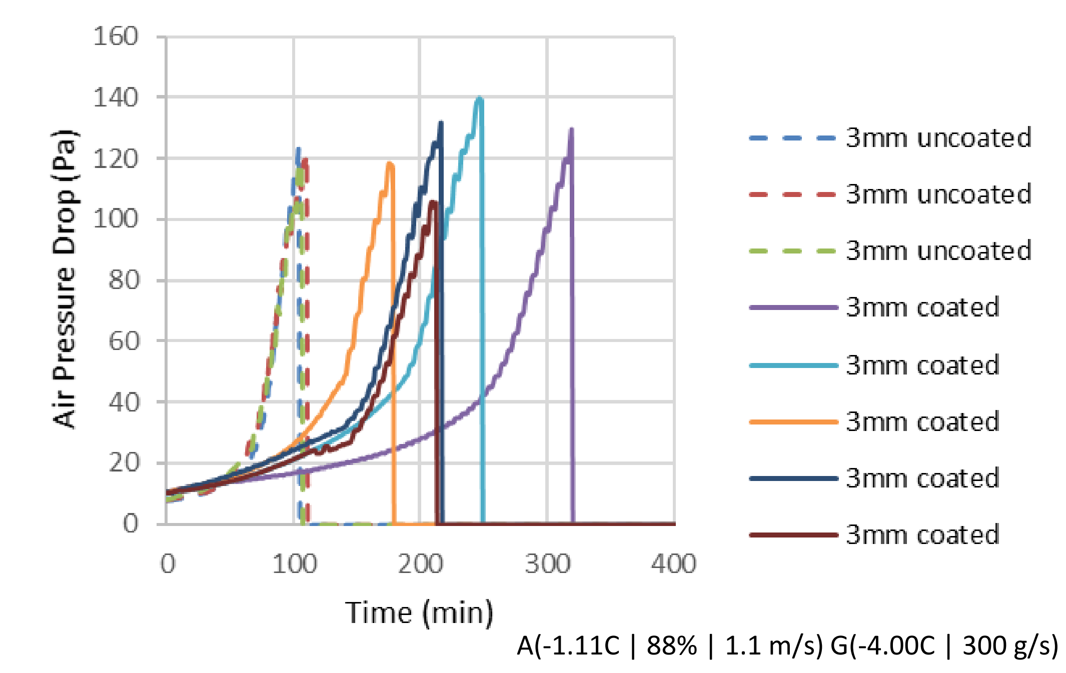


Effect of Coatings

3mm coils



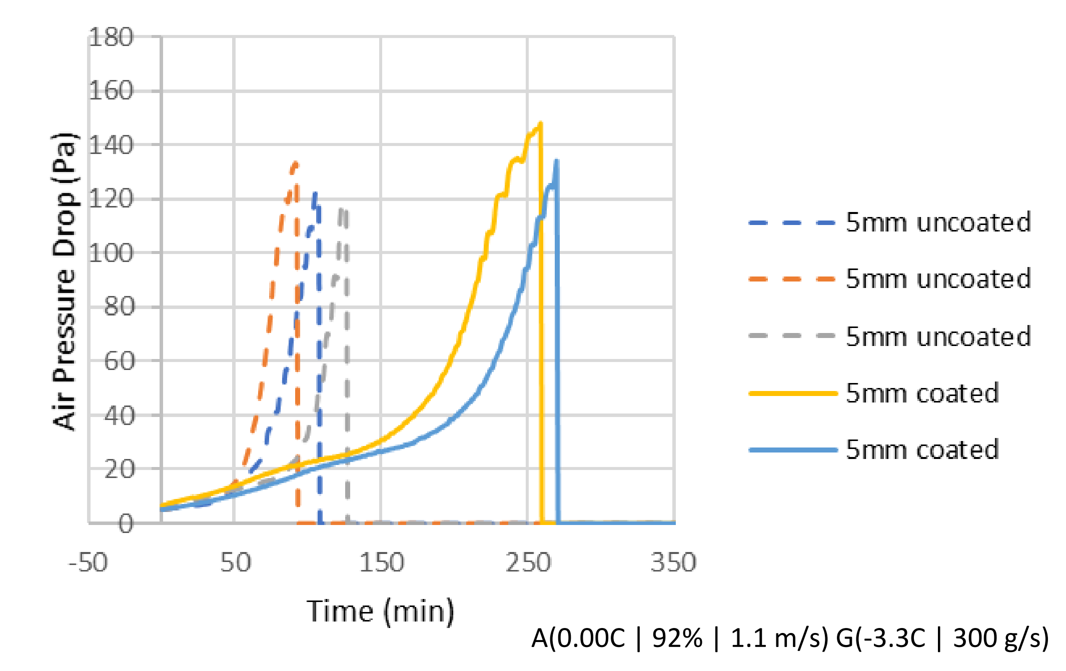
125-185% improvement



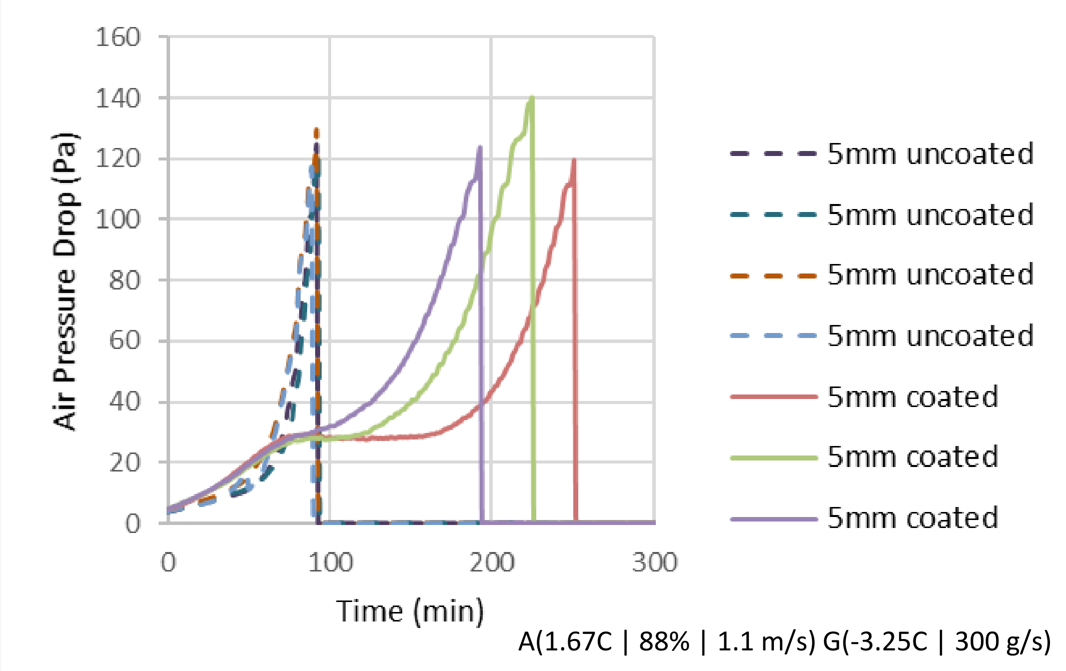
58-207% improvement

Effect of Coatings (cont.)

5mm coils



109-193% improvement



108-182% improvement

Effect of Coatings (cont.)

- **Percent Improvement under each frost test condition**

3mm

Frost Test	% Improvement Range
1	-6 to 80
2	-8 to 538
3	365 to 523
4	125 to 185
5	165 to 290
8	58 to 207
9	6 to 291

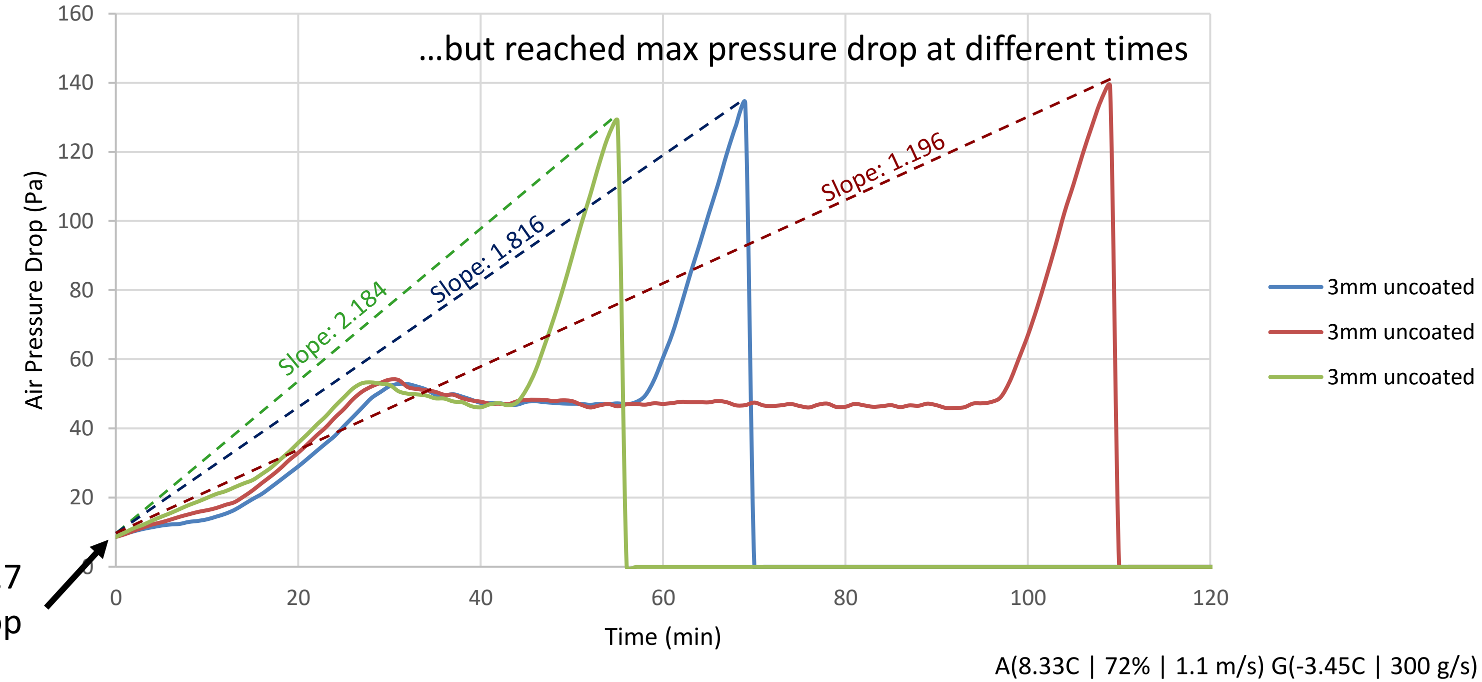
5mm

Frost Test	% Improvement Range
1	23 to 65
2	108 to 182
3	76 to 174
4	109 to 193
5	77 to 89
8	-31 to -6
9	-26 to 34

Repeatability

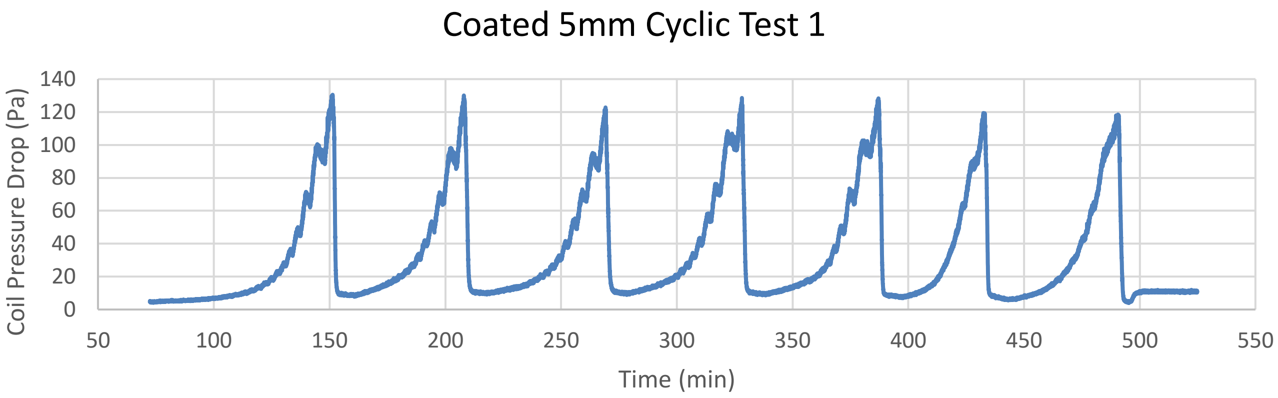
- **Frost tests are highly variable**
- **Small changes in operating conditions can produce very different results**

All 3 tests started at 8.7 Pa air pressure drop

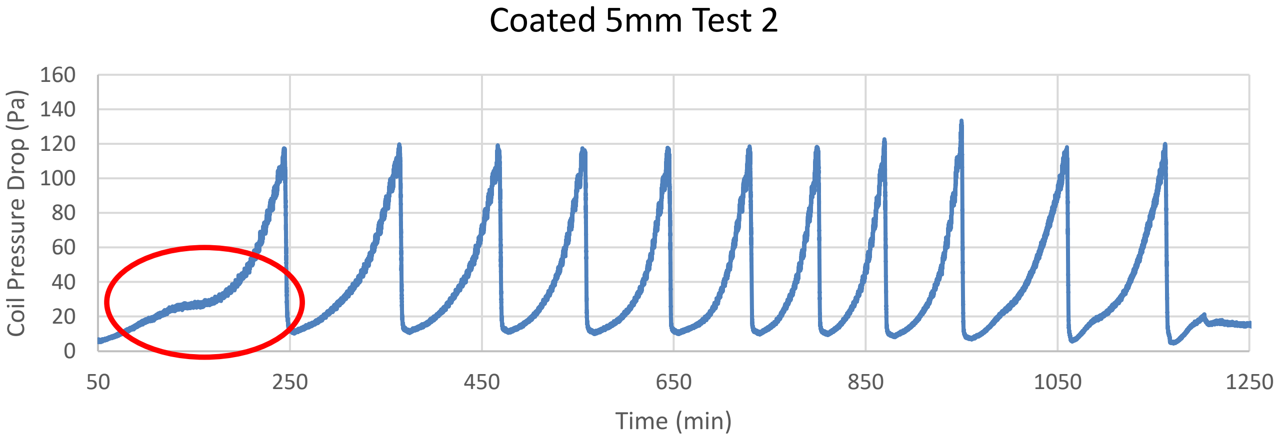


Cyclic Testing

- Ideally, tests should be repeated through multiple cycles because coil usually doesn't return to 100% dry state
- Some test conditions are more sensitive to repeatability issues



Cycle	Peak Pressure (Pa)	Time at Peak Pressure (min)	Time Between Peaks (min)
1	131	151	
2	130	208	57
3	123	269	61
4	129	328	59
5	127	387	59



Cycle	Peak Pressure (Pa)	Time at Peak Pressure (min)	Time Between Peaks (min)
1	117	245	
2	120	364	119
3	119	467	103
4	117	555	88
5	117	645	90
6	118	729	84
7	118	799	70

Conclusions/Discussion

- 3mm designs offer clear advantages over larger diameters, even 5mm
- Frost tests were performed to begin to understand differences in frost development for such small diameters
- 3mm has smaller characteristic lengths and frosts degrades performance more quickly
- Superhydrophobic coatings may be helpful in mitigating frost effects
  - Other coatings exist and may perform better – potential for future work
- Frost tests are highly variable, repeated cyclic tests and tightly controlled conditions are required
  - This type of testing allows for qualitative study and materials screening
  - System-level testing is gold standard for determining real world impacts

Questions

Contact: Nasuta@optimizedthermalsystems.com