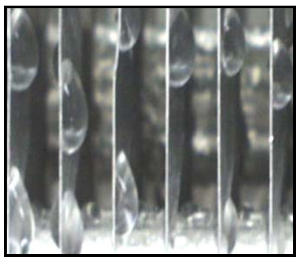
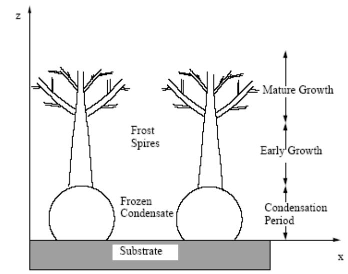
Using Surface Wettability to Impact the Frost Properties and Defrosting Effectiveness of a Metallic Heat Transfer Surface

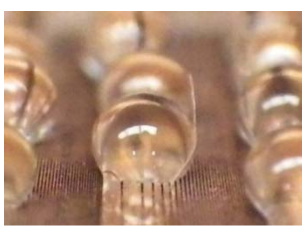




Nicholas Truster[1], Catherine Puleo[2],
Dr. Edgar Caraballo[1], Dr. Andrew Sommers[1,*]

[1]Department of Mechanical and Manufacturing Engineering
Miami University / Oxford, OH 45056

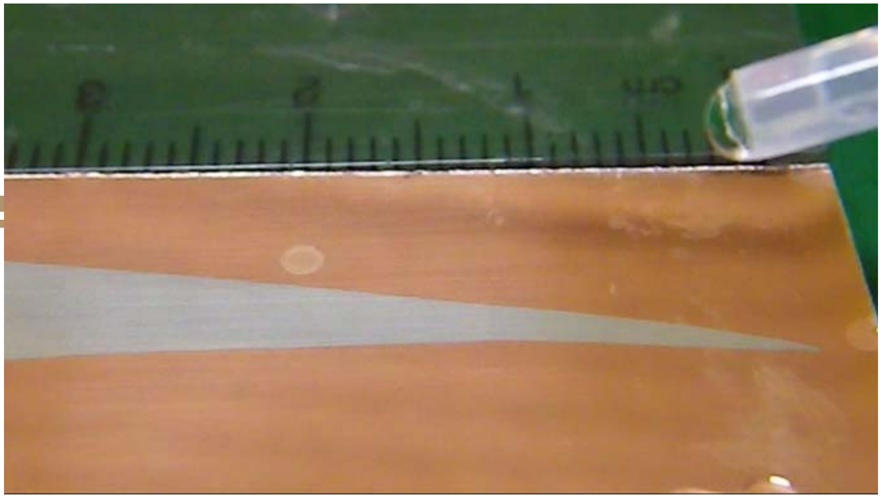
[2]Department of Chemical, Paper, and Biomedical Engineering
Miami University / Oxford, OH 45056



July 17, 2014

MIAMI UNIVERSITY
College of Engineering and Computing

Outline

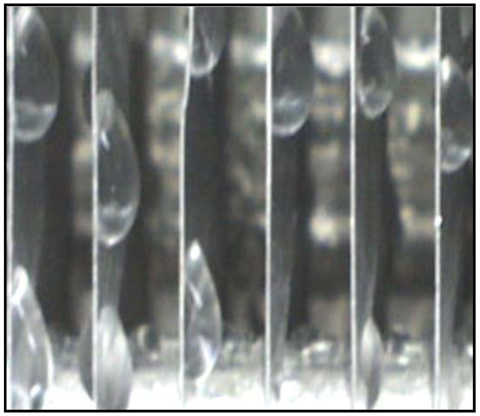


Spontaneous Motion of a Water Droplet on a Wedge-Shaped Gradient

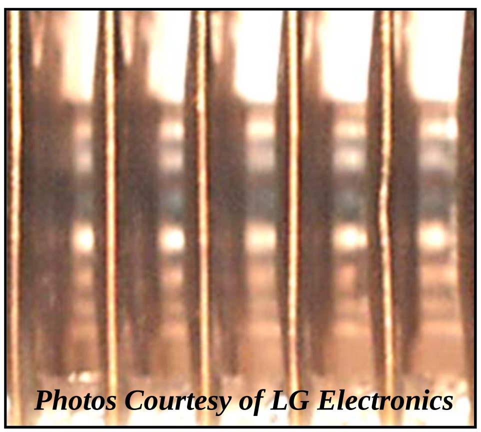
- ❑ Background and Motivation
  - ➢ What are gradient surfaces?
- ❑ Experimental Methodology
- ❑ Effect of Surface Wettability on Frost Properties
  - ➢ Can wettability be used to affect the frost density, thickness, etc.?
- ❑ Effect of Surface Wettability on Defrosting Effectiveness
  - ➢ Can wettability be used to facilitate increased water removal for multiple defrost cycles without degradation?
- ❑ Conclusions and Future Work

Background and Motivation

condensate droplets



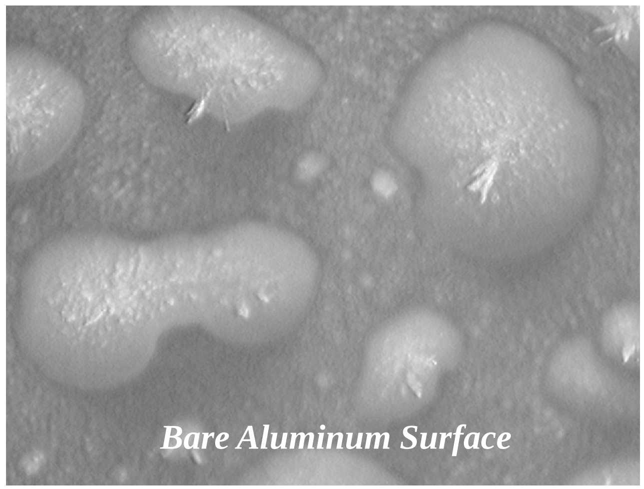
condensate film



Photos Courtesy of LG Electronics

← Air-Conditioning Systems

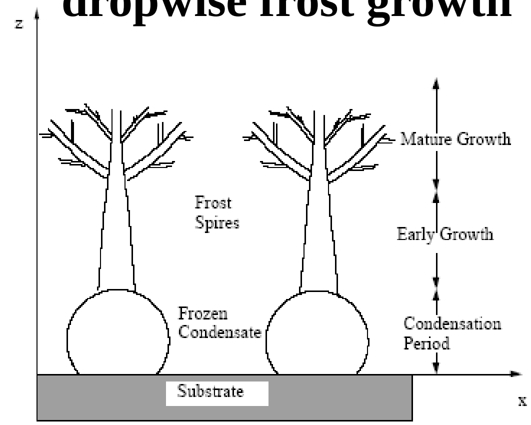
Refrigeration Systems →



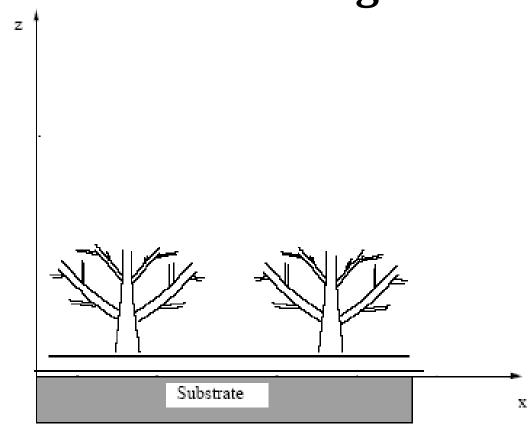
Bare Aluminum Surface

Surface wettability not only affects the mode of condensation on the fin surface but also the overall distribution and retention of water.

dropwise frost growth

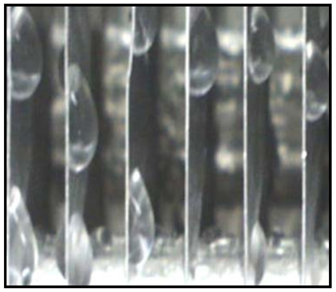


filmwise frost growth



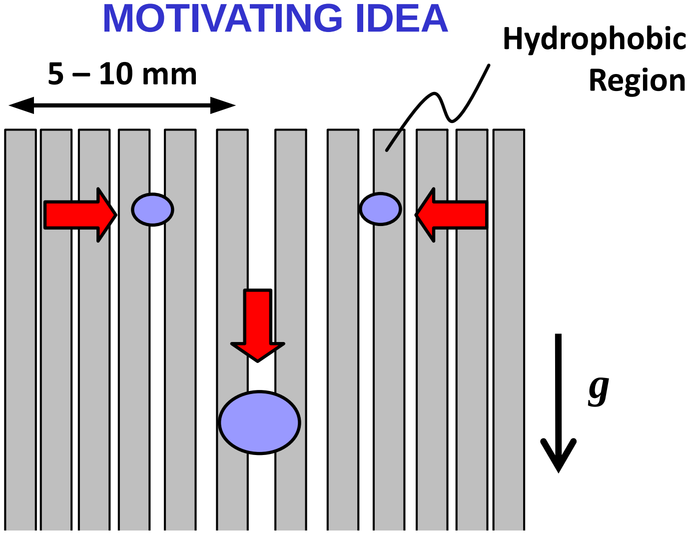
Background and Motivation

- **Aluminum and copper are widely used in heat transfer surface design**
  - Low cost w/ excellent mechanical and thermal properties
  - However, both materials are naturally hydrophilic
- **Water retention in refrigeration systems (after defrosting)**
  - Leads to ice formation which can accelerate frost growth
  - Promotes air flow blockage and shortens the defrost interval
- Typical approaches used to address this problem (fin staging, hot gas defrost, etc.) constitute inefficiencies in the system
- Surface tension gradients could be used to impart directionality to the surface and facilitate the removal of droplets too small to otherwise drain.



Heat Exchanger Fins

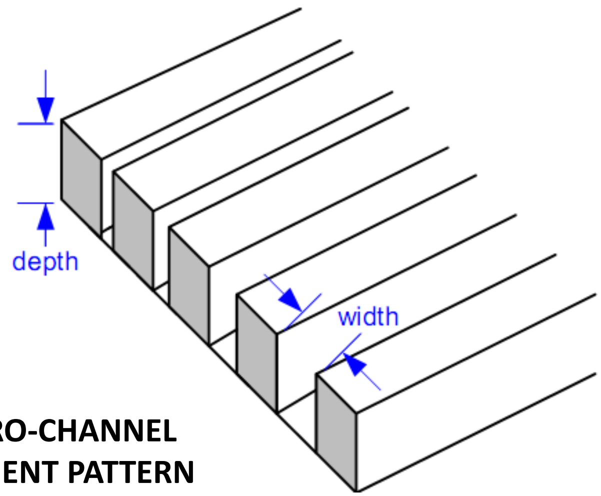
MOTIVATING IDEA



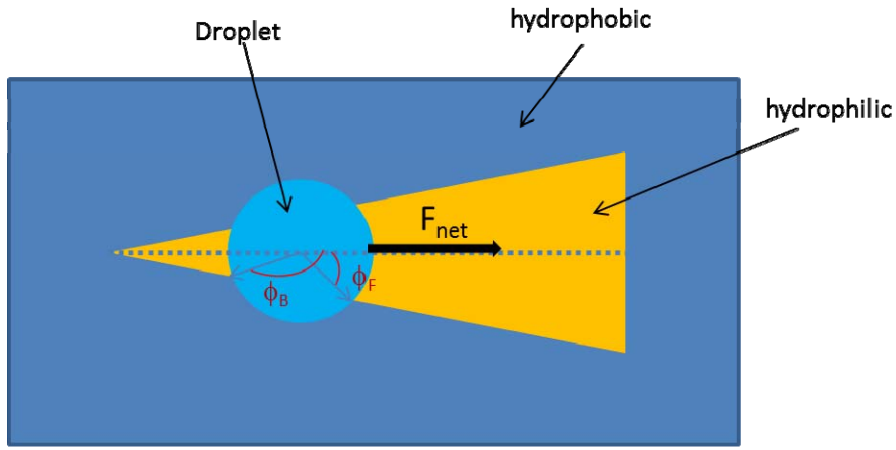
Perhaps surface tension gradients could be used to cause water droplets (too small to otherwise drain) to move a short distance and coalesce with each other?

Surface Tension Gradients

- ***What is a surface tension gradient?***
  - A transition in wettability from hydrophobic to hydrophilic that produces a net capillarity force that can be used for actuating droplets a short distance.
  - Spontaneous droplet movement (including uphill) was first demonstrated experimentally by Chaudhury and Whitesides (1992).
  - Gradients can be created using chemistry and/or topography-based approaches.

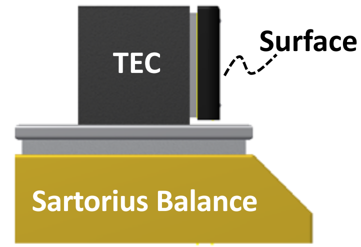


MICRO-CHANNEL GRADIENT PATTERN (Sommers et al., 2013)



TRIANGULAR WEDGE GRADIENT PATTERN (Alheshibri et al., 2013)

Experimental Methodology



- Frost was grown on prepared surfaces under environmentally-controlled conditions and then periodically defrosted.
- Two types of tests were performed:
  - ❖ **Frost Properties** – three hour continuous growth followed by 10 min defrost
  - ❖ **Cycling Tests** – one hour growth + 8 min defrost period (repeated 3x)
- Surface temperature was prescribed using a thermoelectric cooler (TEC) and monitored using T-type thermocouples inserted into the sample
- Ultrasonic humidifier used to maintain constant relative humidity (60-80%) inside the enclosure
- CCD camera recorded frost layer on fixed interval
- High-precision balance connected to a computer was used to record the frost mass in real time (Note: No sample transfer needed.)

Table 1: Matrix of Test Conditions

Test Condition A 60% RH 16.0V or -3ºC	**Test Condition B** 60% RH 18.6V or -6ºC	**Test Condition C** 60% RH 22.0V or -9ºC
Test Condition D 80% RH 16.0V or -3ºC	**Test Condition E** 80% RH 18.6V or -6ºC	**Test Condition F** 80% RH 22.0V or -9ºC

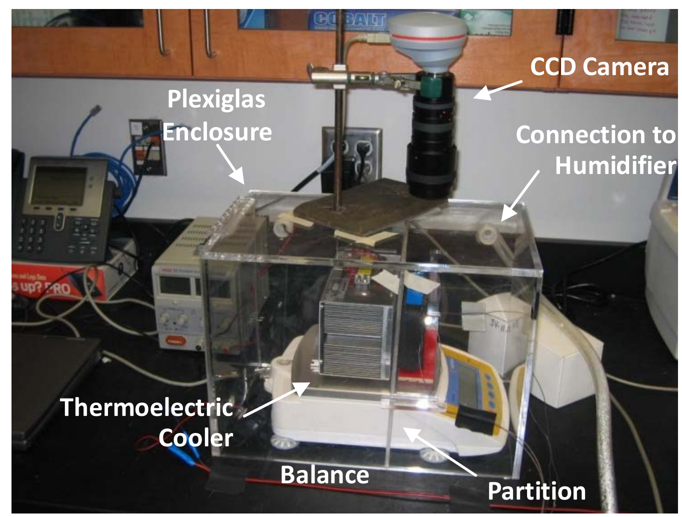
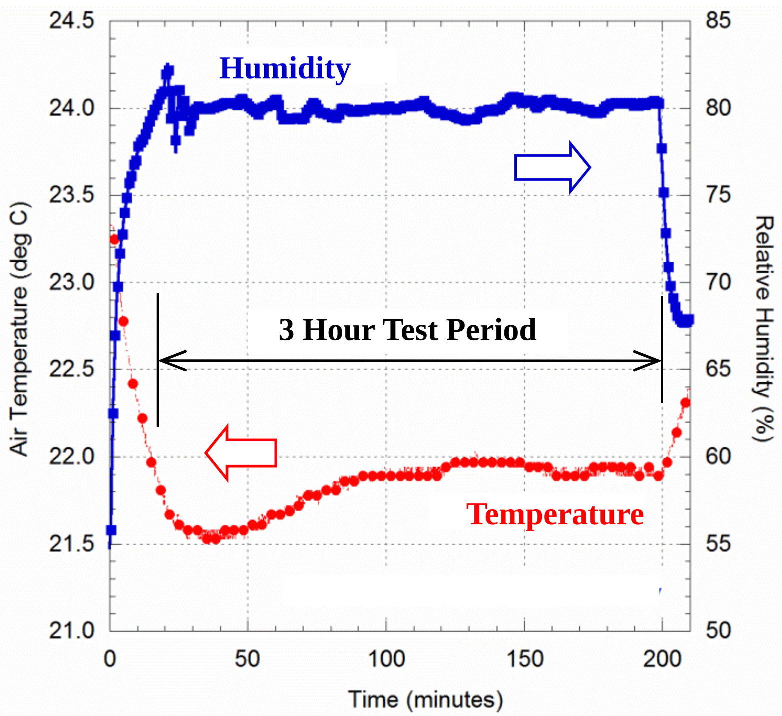


Fig 1: Picture of Experimental Setup

Experimental Methodology

- Relative humidity was maintained to within ±3% inside the enclosure, and the air temperature was typically constant to within ±0.5ºC.
- The surface temperature was set by fixing the voltage supplied to the TEC.



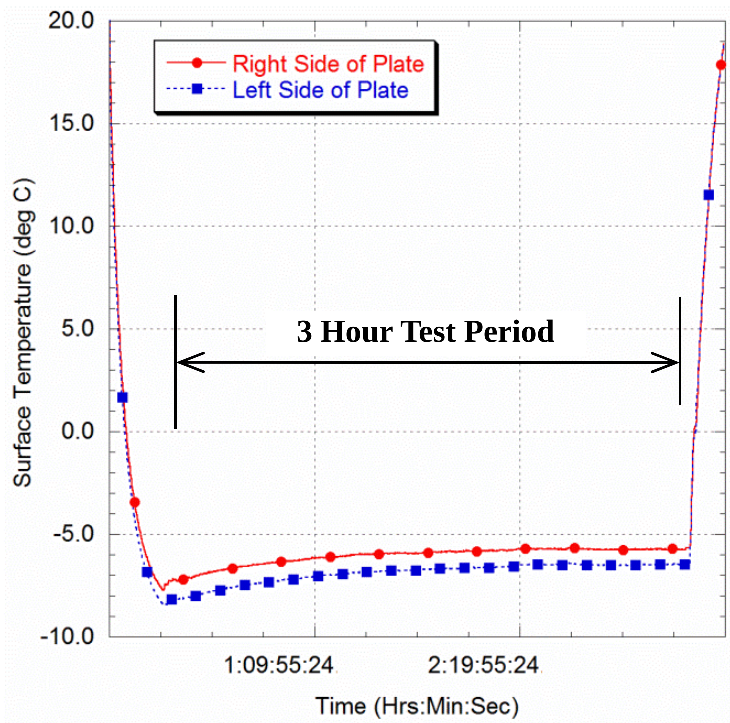


Fig 2: Environmental conditions during a 80% RH, 18.6V TEC test (**typical**)

Experimental Methodology

Table 2: Matrix of Heat Transfer Test Surfaces

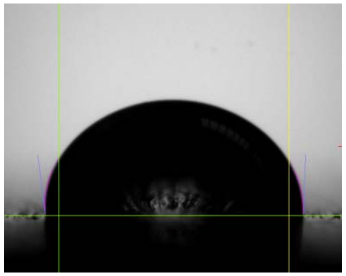
No.	Material	Gradient	Surface Features	Method
1	Al	N	None	--
2	Al	N	Hydrophobic Coating (NeverWet™ spray-on coating)	Spray Coating
3	Al	Y	Hydrophobic / Hydrophilic Wedges (Cu layer with SAM coating)	Metal Deposition
4	Al	Y	Laser Etched Radial Design (in progress)	Laser Machining

Table 3: Contact Angles on Test Plates

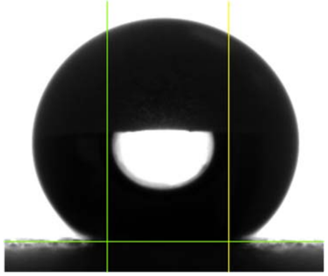
No.	Surface	Contact Angle
1	Baseline Surface	98.4º (*n* > 25)
2	Hydrophobic Surface (after testing)	151.5º (*n* > 25)
	Hydrophobic Surface (not used in testing)*	156.5° (*n* > 25)

* For comparison only. Small decrease in CA was observed.

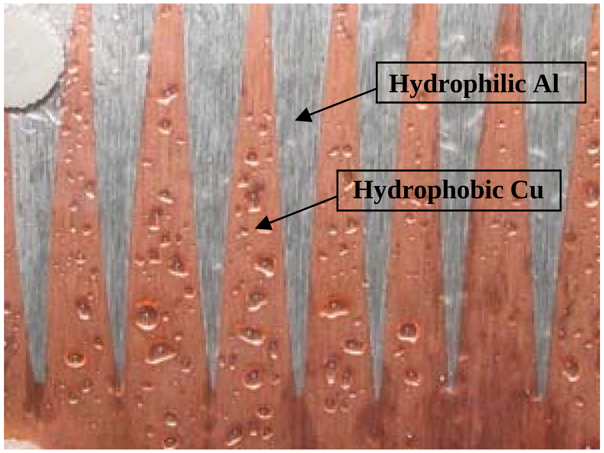
- Al 5052 plates (brushed finish) – 99.5 × 80.2 × 3.4 mm in size; held to TEC stage using thermal paste and four nylon screws w/ Teflon spacers
- Rame-hárt goniometer was used to measure the contact angles



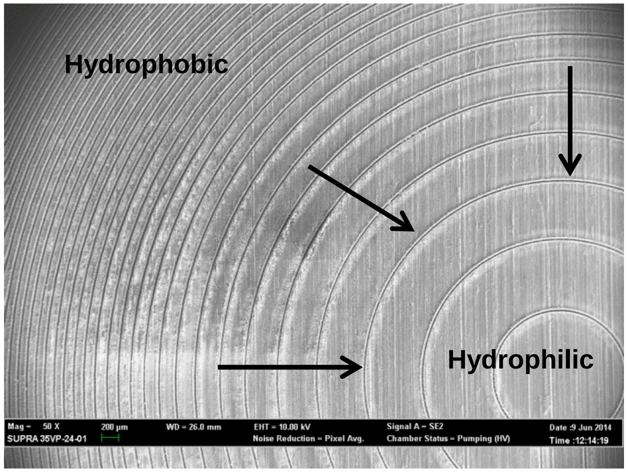
Surface 1



Surface 2



Surface 3 Wedge Pattern



Surface 4 Radial Design

Results and Discussion

Frost Property Testing (Thickness)

- Frost thickness was determined by pixel counting against a calibrated image.
- The thickness scaled inversely with surface temp but directly with relative humidity.
- This behavior is consistent w/ Hayashi (1977) who found that thinner, denser frost layers formed on warmer surfaces & thicker frost layers formed on colder surfaces.

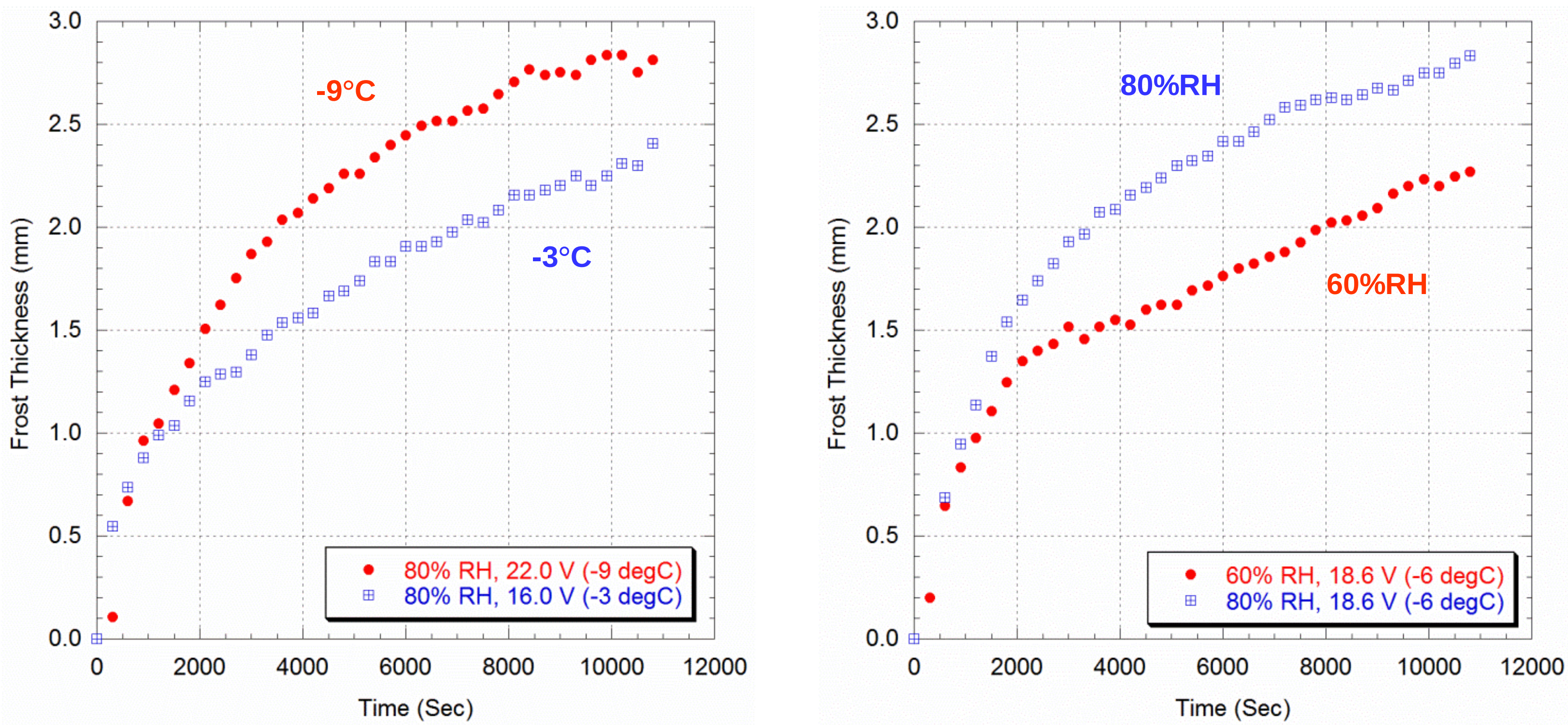


Fig 3: Effect of surface temperature and relative humidity on frost thickness for Sample 1 (baseline)

Frost Property Testing (Frost Mass)

Frost mass was also higher at 80% RH than at 60% RH on the baseline surface as might be expected. Also noteworthy is the fact that while the frost thickness increased nonlinearly with time, the frost mass increased linearly with time.

This suggests that the condensing water vapor contributed both to increasing the frost density as well as to increasing the frost thickness— something that has been observed by others (Östin and Andersson, 1991).

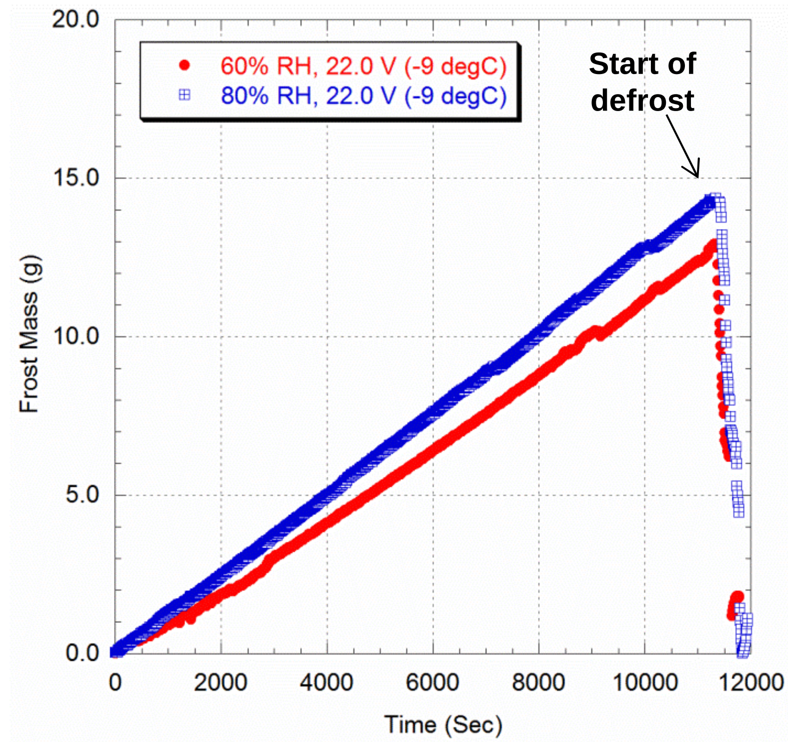
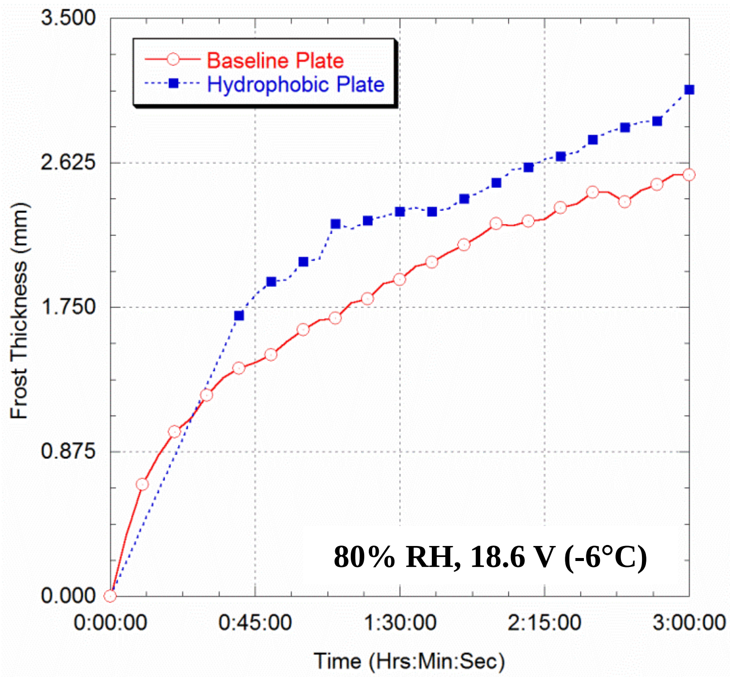


Fig 4: Effect of relative humidity on the deposited frost mass for Sample 1

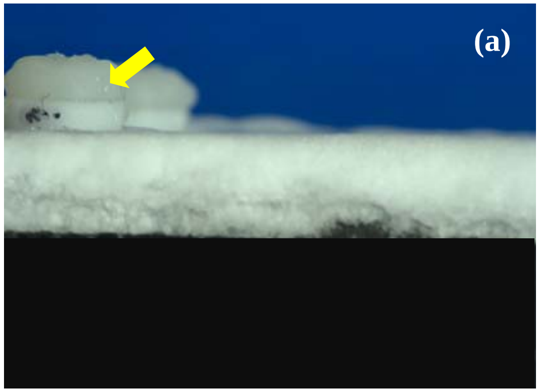
Frost Property Testing (Sample 1 vs 2)



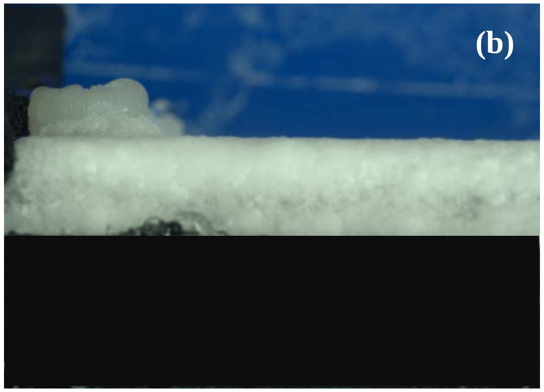
∴ The frost layer was **thicker** on the hydrophobic surface versus the baseline surface.

These images were both taken at approx. 150 min into the experiment under the same conditions (80% RH, 22.0V TEC). Differences in frost thickness can be seen by comparing the frost height to the nylon screw at the left. Markings were made on the screw every 1 mm.

The frost thickness on Sample 1 is less than 3 mm while the frost layer on Sample 2 is ≥ 3 mm thick.

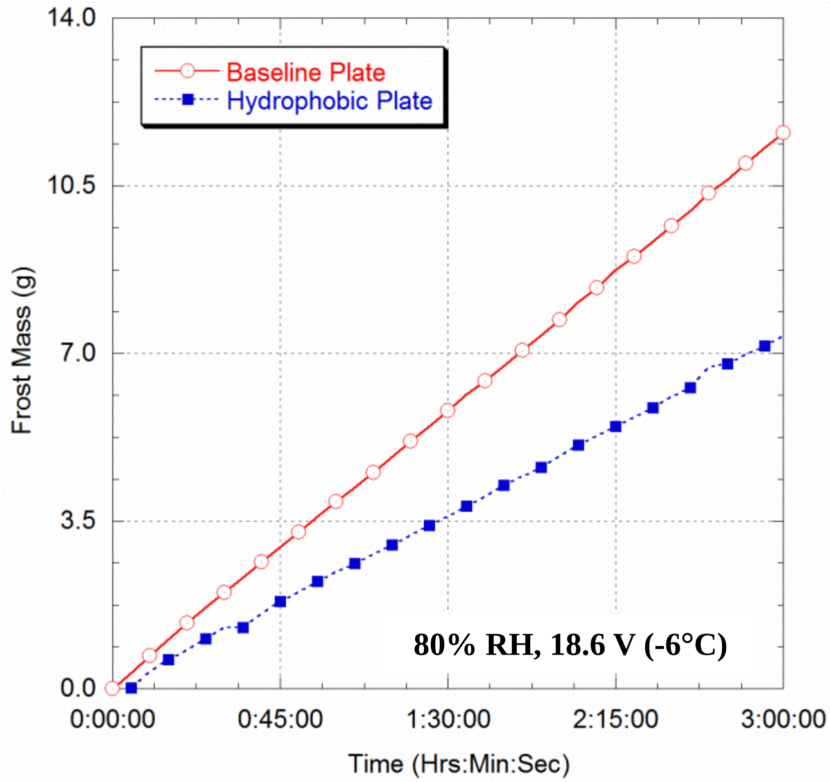


Sample 1: Baseline Surface

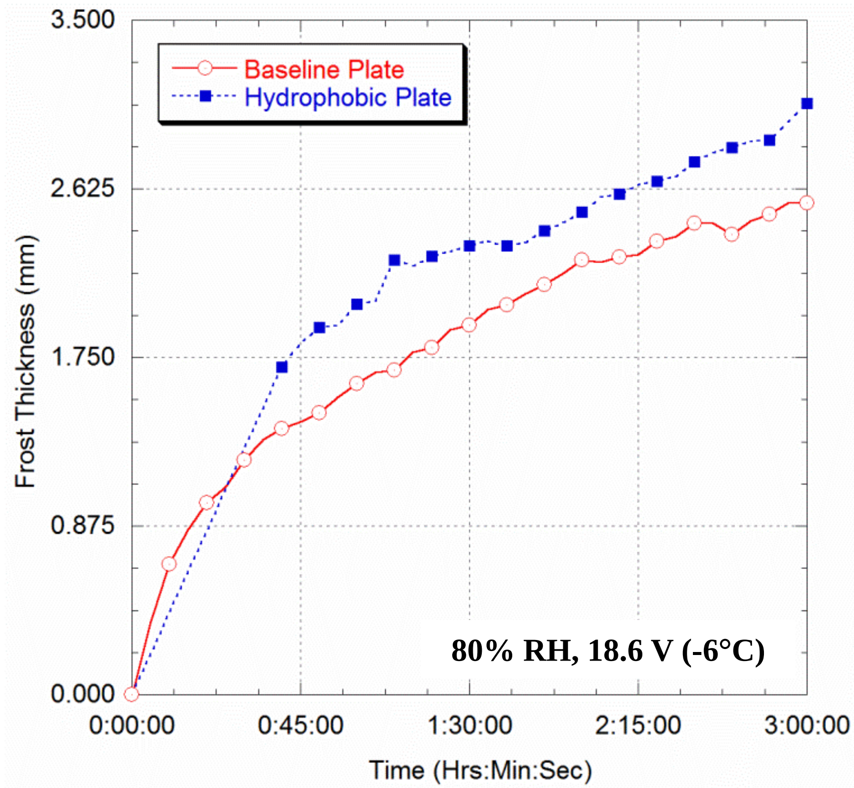


Sample 2: Hydrophobic Surface

Frost Property Testing (Sample 1 vs 2)

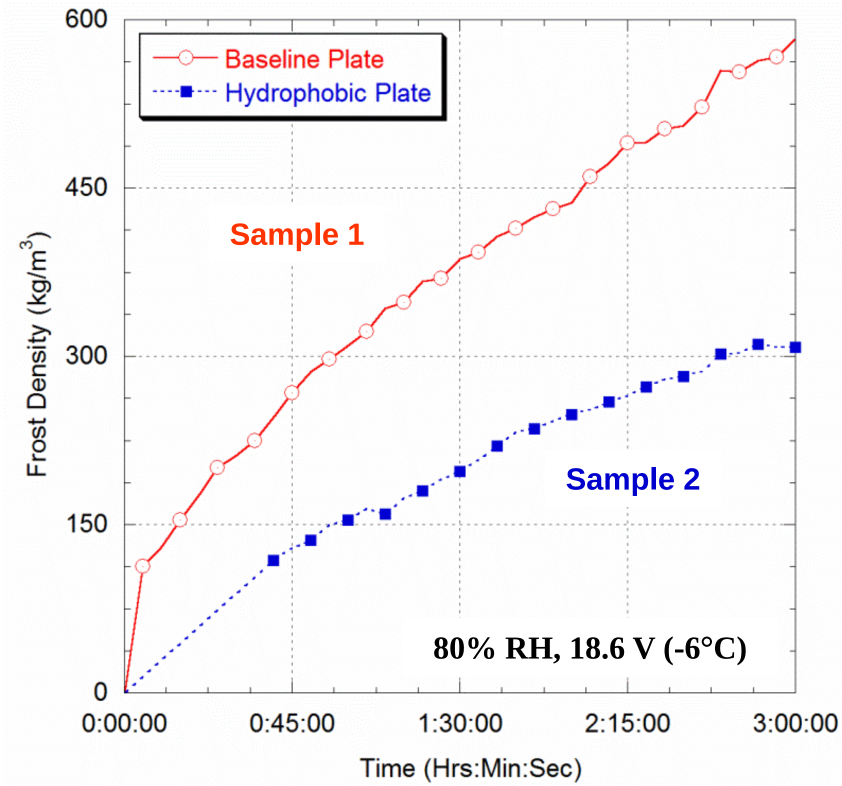


Frost Mass ~60% HIGHER on Sample 1 (Baseline Surface)



Frost Thickness ~20% LOWER on Sample 1 (Baseline Surface)

Frost Property Testing (Sample 1 vs 2)



Frost Density ~80-90% HIGHER on Sample 1 (Baseline Surface)

∴ Frost Density was lower on the hydrophobic surface!

Defrost Cycling Tests

- **Test Procedure:** 60 min frosting + 8 min defrosting; repeated three times
- Two metrics were used to measure the surface's performance. The second metric was defined to account for small differences in the defrosting time (actual).
  - ***Defrosting percentage, %*** - mass of drained water / initial mass of frost on the surface
  - ***Defrosting effectiveness,*** Φ - ratio of drained water mass to initial frost mass X ratio of frosting time to defrosting time

METRIC 1: Defrosting Percentage

$$\% = \frac{m_{\text{removed}}}{m_{\text{initial}}}$$

METRIC 2: Defrosting Effectiveness

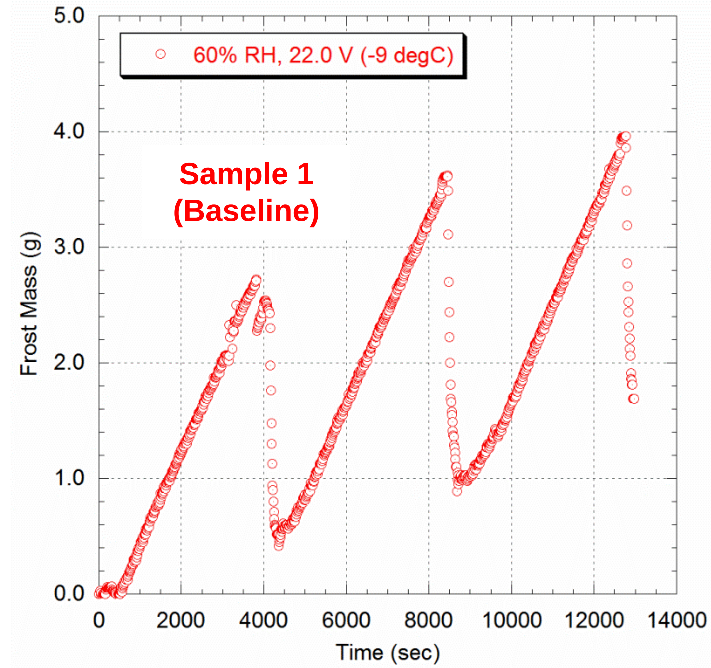
$$\Phi = \frac{(m_{\text{removed}}) \times (t_{\text{frost}})}{(t_{\text{defrost}}) \times (m_{\text{initial}})}$$

$$\text{where } t_{\text{frost}} = 3600\text{s}$$

NOTE: Larger Φ values mean more efficient defrosting.

Defrost Cycling Tests

- Defrosting efficiency degradation was observed on Sample 1 (baseline surface).
- Sample 2 exhibited the best defrosting performance of all the surfaces tested to date (i.e. 24-26% increase over the baseline surface).
- The defrosting efficiency for Sample 2 was constant over 3 cycles (unlike the other surfaces).
- Sample 3 exhibited a high defrost efficiency in the first cycle but then performed similar to the baseline surface in subsequent cycles.



No.	Frosting/Defrosting Conditions	Sample 1 (Baseline)	Sample 2 (Hydrophobic)	Sample 3 (Wedge Shape)
1	60% RH, 22.0V Cycle 1	**Φ = 5.824**	**Φ = 7.315**	**Φ = 6.785**
		80.9%	n/a*	94.2%
2	60% RH, 22.0V Cycle 2	**Φ = 5.358**	**Φ = 6.635**	**Φ = 5.540**
		72.9%	n/a*	76.9%
3	60% RH, 22.0V Cycle 3	**Φ = 6.182**	**Φ = 7.686**	**Φ = 6.186**
		56.7%	n/a*	55.0%

* Defrosting time was slightly different than other samples.

$$\% = \frac{m_{\text{removed}}}{m_{\text{initial}}}$$

$$\Phi = \frac{(m_{\text{removed}})\times(t_{\text{frost}})}{(t_{\text{defrost}})\times(m_{\text{initial}})}$$

where $t_{\text{frost}} = 3600\text{s}$

NOTE: Larger Φ values = improved defrosting

Conclusions

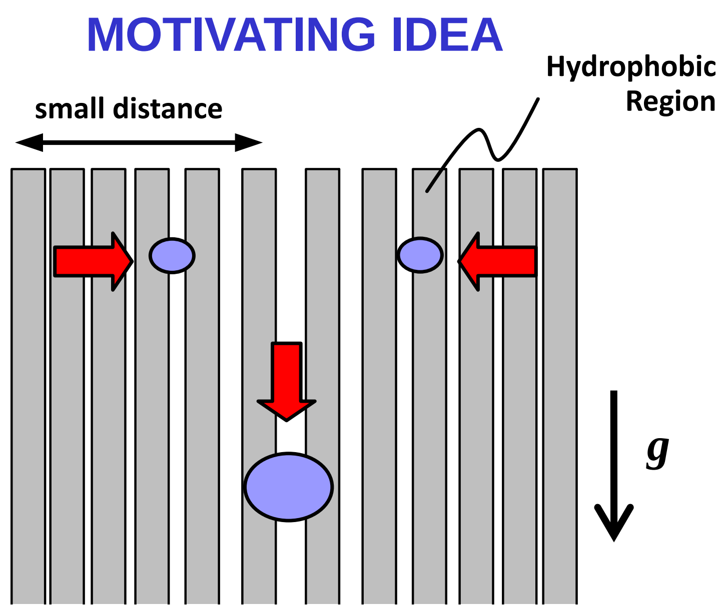
- Frost thickness was slightly <u>higher</u> on the hydrophobic surface (Sample 2) than the baseline aluminum surface (Sample 1) but the difference remained fairly constant beyond the early frost growth period suggesting that this could potentially be accounted for during the initial design of the HX.

- Frost mass and density were both generally <u>lower</u> on the hydrophobic surface. This could be an advantage or disadvantage depending on the application.

- Two metrics were used to measure surface defrosting performance.
  - ***Sample 1 (baseline)*** exhibited defrosting % degradation with each cycle
  - ***Sample 2 (hydrophobic)*** showed defrosting performance that was approximately <u>24-26% better than the baseline</u> and more consistent. The long-term reliability of the coating however is still unknown.
  - ***Sample 3 (wedge shape)*** exhibited very good defrosting performance during the 1st cycle (better than baseline) but afterwards its performance was similar to the baseline.

Conclusions

- Additional tests are currently underway to explore the potential benefits of using **<u>surface tension gradients</u>** to facilitate the movement of droplets to preferred locations on the surface for increased coalescence and drainage.



Could gradients be used to cause droplets (too small to otherwise drain) to move a short distance and coalesce with another droplet?

Bibliography

- Alheshibri, M.D., Rogers, N.G., Sommers, A.D., Eid, K.F., 2013, “Spontaneous movement of water droplets on patterned Cu and Al surfaces with wedge-shaped gradients,” ***Appl. Phys. Lett. 102,*** 174103.
- Sommers, A.D., Brest, T.J., Eid, K.F., 2013, “Topography-Based Surface Tension Gradients to Facilitate Water Droplet on Laser-Etched Copper Substrates,” ***Langmuir 29,*** 12043-12050.
- Sommers, A.D., Yu, R., Okamoto, N.C., Upadhyayula, K., 2012, “Condensate drainage performance of a plain fin-and-tube heat exchanger constructed from anisotropic, micro-grooved fins,” ***Int. J. Refrigeration 35***, pp. 1776-1778.
- Yu, R., Sommers, A.D., Okamoto, N.C., 2013, “Effect of a micro-grooved fin surface design on the air-side thermal-hydraulic performance of a plain fin-and-tube heat exchanger,” ***Int. J. Refrigeration 36***, pp. 1078-1089.

For additional information:

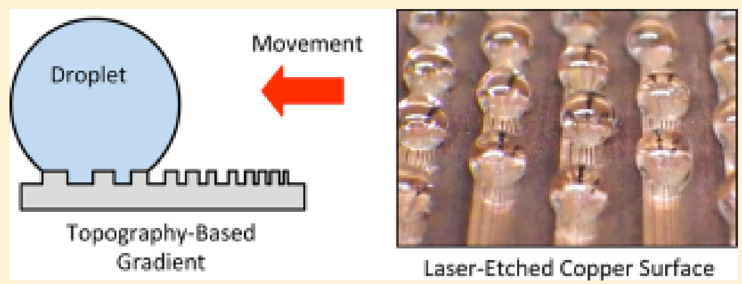
Topography-Based Surface Tension Gradients to Facilitate Water Droplet Movement on Laser-Etched Copper Substrates

A. D. Sommers,*,† T. J. Brest,‡ and K. F. Eid‡

†Department of Mechanical and Manufacturing Engineering, Miami University, 56 Garland Hall, Oxford, Ohio 45056, United States
‡Department of Physics, Miami University, 35 Culler Hall, Oxford, Ohio 45056, United States

Supporting Information

ABSTRACT: This paper describes a method for creating a topography-based gradient on a metallic surface to help mitigate problems associated with condensate retention. The gradient was designed to promote water droplet migration toward a specified region on the surface which would serve as the primary conduit for drainage using only the roughness of the surface to facilitate the movement of the droplets. In this work, parallel microchannels having a fixed land width but variable spacing were etched into copper substrates to create a surface tension gradient along the surface of the copper. The surfaces were fabricated using a 355 nm Nd:YVO4 laser system and then characterized using spray testing techniques and water droplet (2−10 μL) injection via microsyringe. The distances that individual droplets traveled on the gradient surface were also measured using a goniometer and CCD camera and were found to be between 0.5 and 1.5 mm for surfaces in a horizontal orientation. Droplet movement was spontaneous and did not require the use of chemical coatings. The theoretical design and construction of surface tension gradients were also explored in this work by calculating the minimum gradient needed for droplet movement on a horizontal surface using Wenzel's model of wetting. The results of this study suggest that microstructural patterning could be used to help reduce condensate retention on metallic fins such as those used in heat exchangers in heating, ventilation, air-conditioning, and refrigeration (HVAC&R) applications.



Sommers et al., 2013, ***Langmuir***, 29, 12043-12050

THANK YOU

Questions?

CONTACT INFORMATION:
E-mail: sommerad@miamioh.edu
Phone: +1 (513) 529-0718