Structured surfaces for anti-frosting

.252

Nicolò G. DI NOVO,[1,2] Matteo OMILLI,[1,2] Alvise BAGOLINI,[2] Damiano GIUBERTONI,[2] Leandro LORENZELLI,[2] Nicola M. PUGNO*,[1,3]

[1]Laboratory of Bioinspired, Bionic, Nano, Meta, Materials & Mechanics, Department of Civil, Environmental and Mechanical Engineering, University of Trento, Trento, Italy
[2]Sensors and Devices Center, Foundation Bruno Kessler, Trento, Italy
[3]School of Engineering and Materials Science, Queen Mary University of London, London, United Kingdom

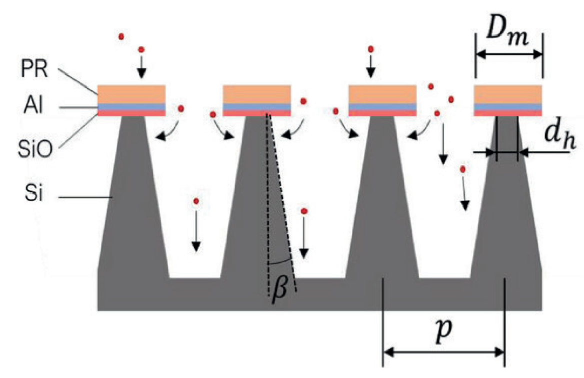
Abstract

Hydrophobic structured surfaces showing coalescence induced condensation droplet jumping (CICDJ) are known to slow down frosting because of unsuccessful ice-bridging events. In a previous study we reported a kind of surfaces structured with truncated microcones covered by uniformly hydrophobic nanostructures that enable single droplet self-ejection [1]. The anti-frosting effect is improved because almost all the droplets self-eject at a precise size and all the ice-bridges are frustrated [2].

We here present these surfaces behavior under different surface temperatures (T) and air relative humidity RH. Higher supersaturation ratio (S) decreases the mean distance between the droplets (l_c). The droplet distance and diameter distributions vary with s and affect the ice-bridging parameter distribution thus frosting velocity. In particular, we analyze the regime change when $l_c \leq$ of the cones unit cell size (*p*) and the CICDJ events prevail on the Self-Ejection ones.

Understanding the effects of environmental conditions on jumping modes (single and multiple droplets) and frost propagation types could lead to an optimal design in terms of cones size and arrangement.

Methods



D_m: 30 μm
p: 40 μm
β: 6 °
d_h: 12.5
H: 64.3 μm

Environmental conditions were varied by adjusting the temperature with two cooling stages. Different degrees of supersaturation ratio S were achieved by modifying the relative humidity RH of an incoming flux of humid air. Analysis aim to determine the ice propagation speed and the density of the first generation of nucleated droplets on the surface.

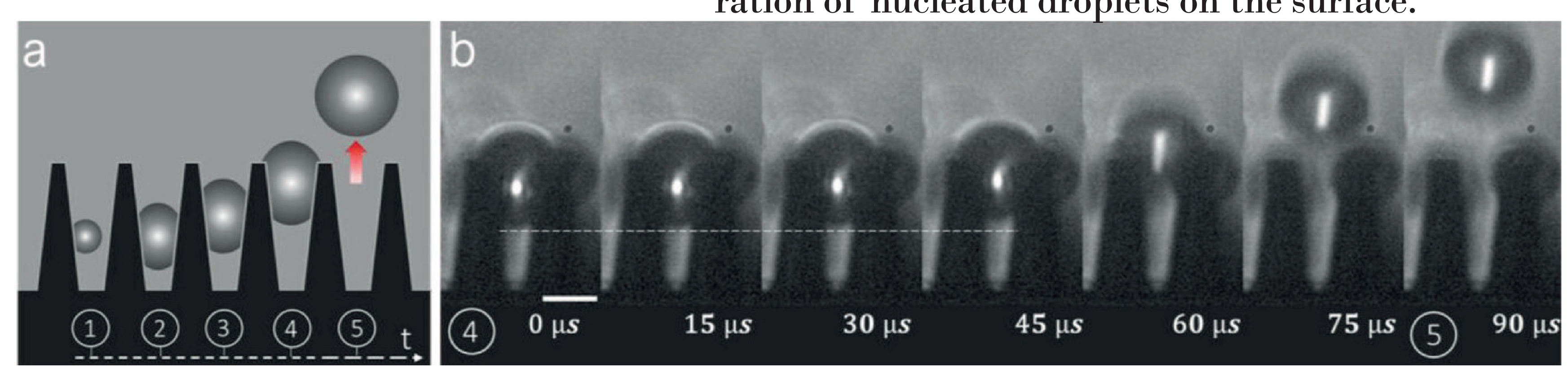
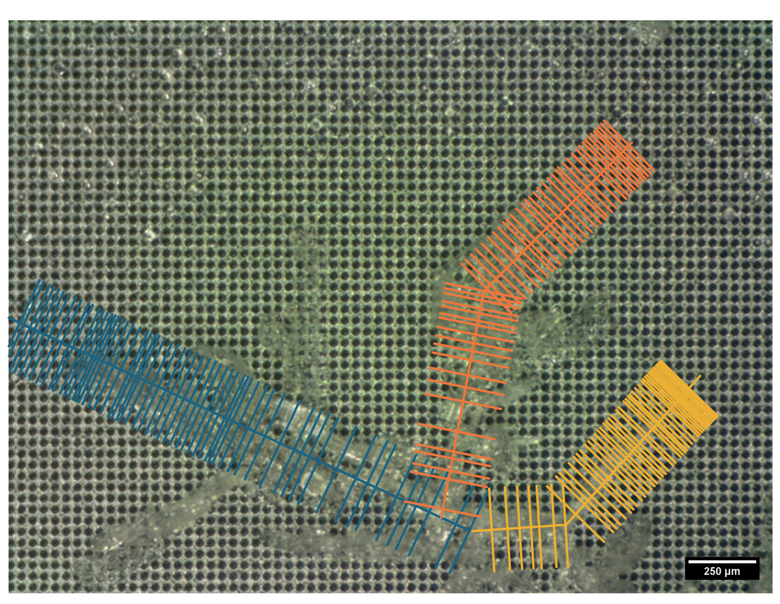


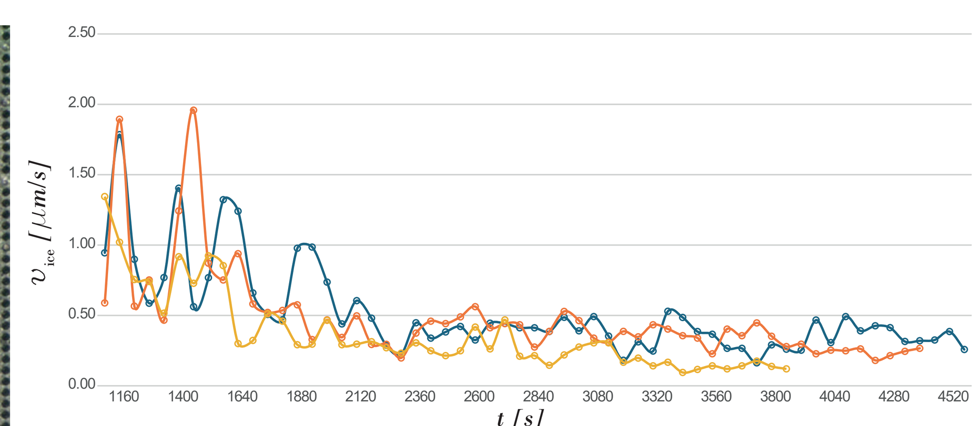
Fig 1. a) The timeline of a condensation droplet from nucleation to self-ejection. b) From 4 to 5 it self-ejects in tens or hundreds of microseconds depending on the structures size

Analysis

T -11 °C

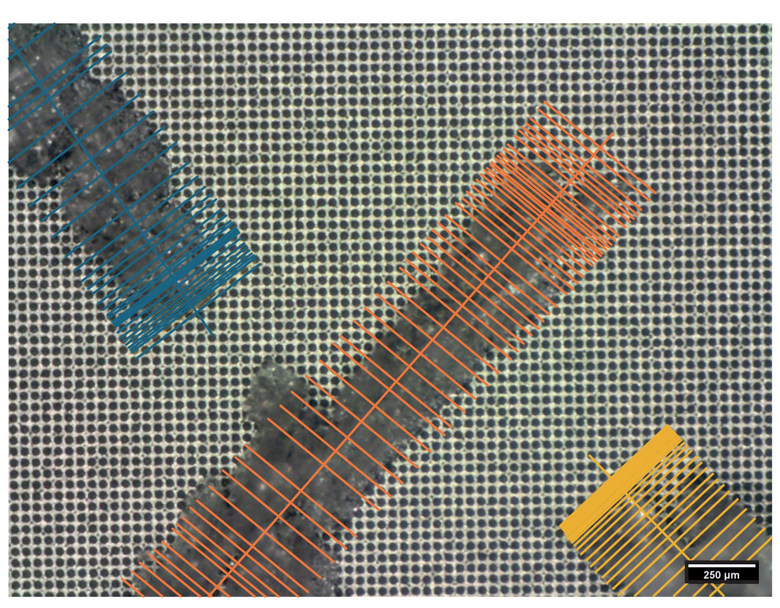
S 2.8

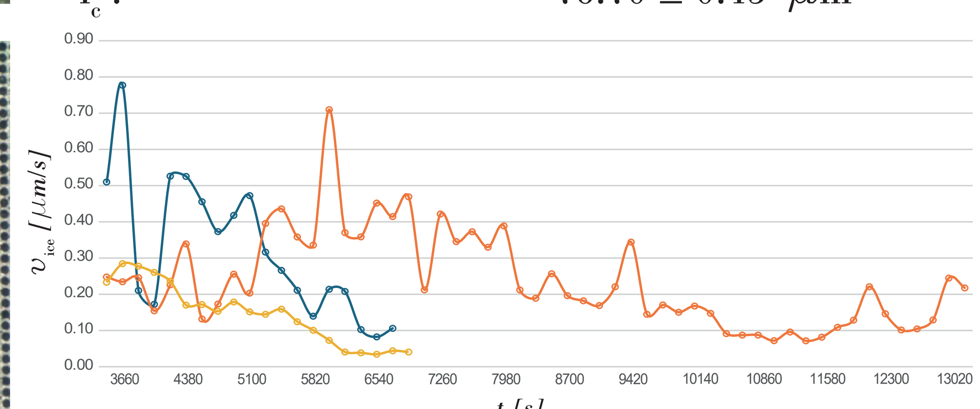




Duration: 00:18:00 to 01:04:00
Ice dendrites speed: 0.15 ± 0.08 μm/s
Droplet Density ρ_c: 170 ± 2 droplets/mm²
l_c: 76.70 ± 0.45 μm

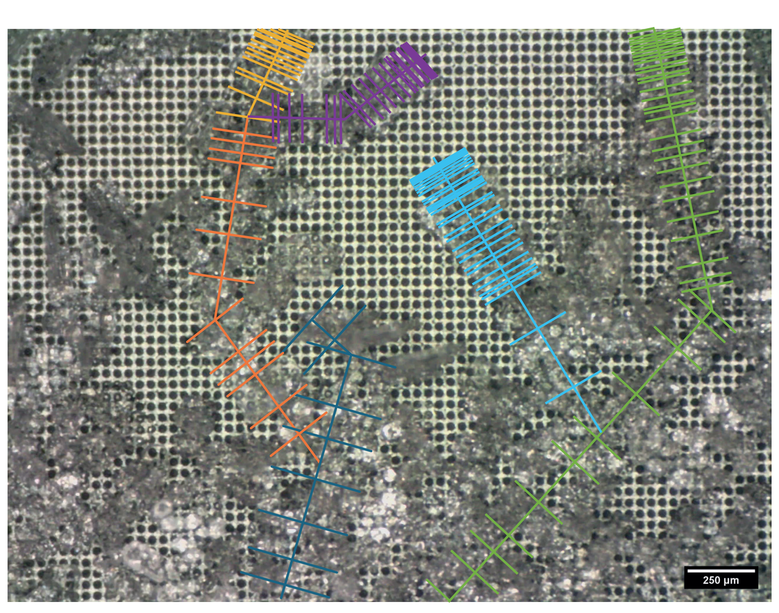
S 4.2

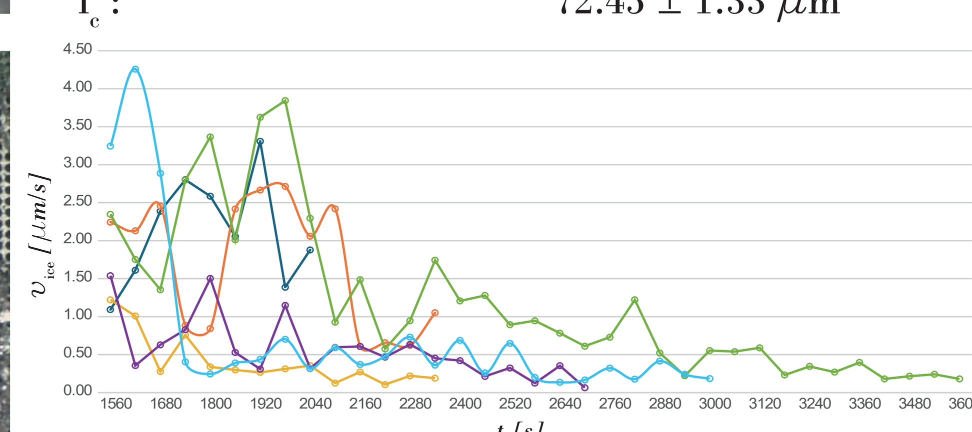




Duration: 01:10:00 to 03:40:00
Ice dendrites speed: 0.23 ± 0.09 μm/s
Droplet Density: 191 ± 7 droplets/mm²
l_c: 72.45 ± 1.33 μm

S 8.4

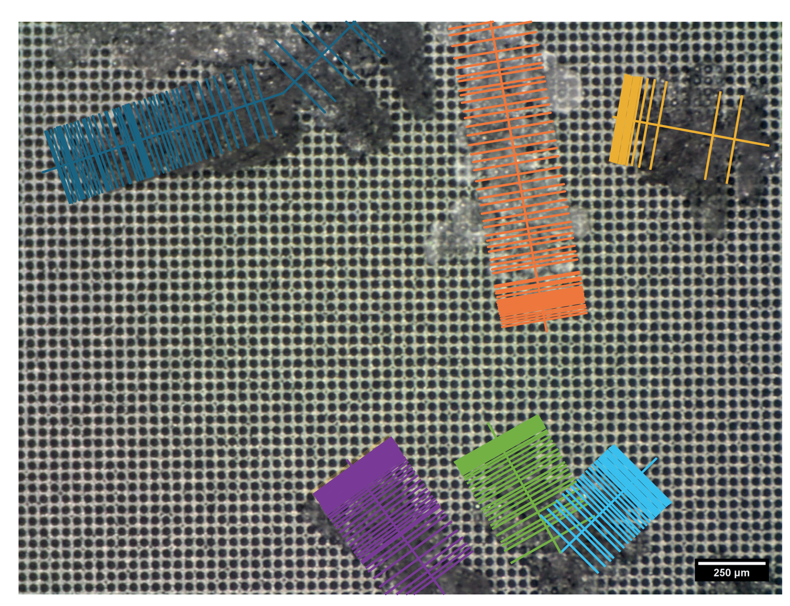


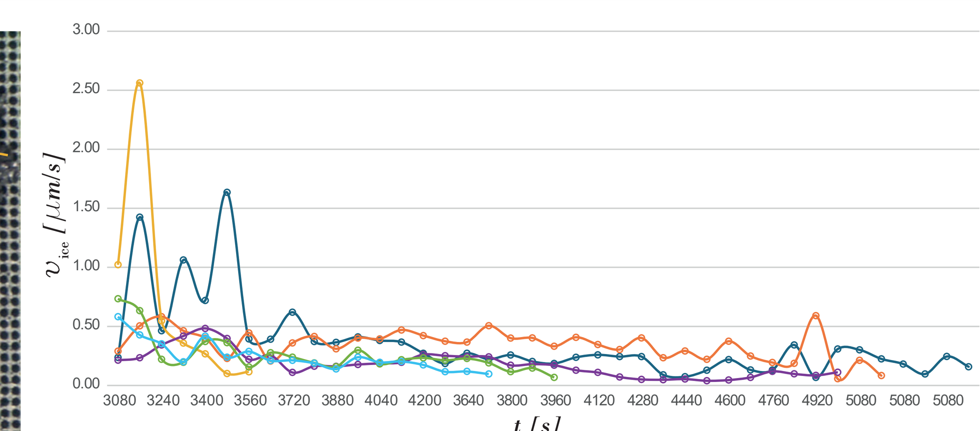


Duration: 00:25:00 to 01:10:00
Ice dendrites speed: 1.12 ± 0.68 μm/s
Droplet Density: 284 ± 7 droplets/mm²
l_c: 59.38 ± 0.73 μm

T -20 °C

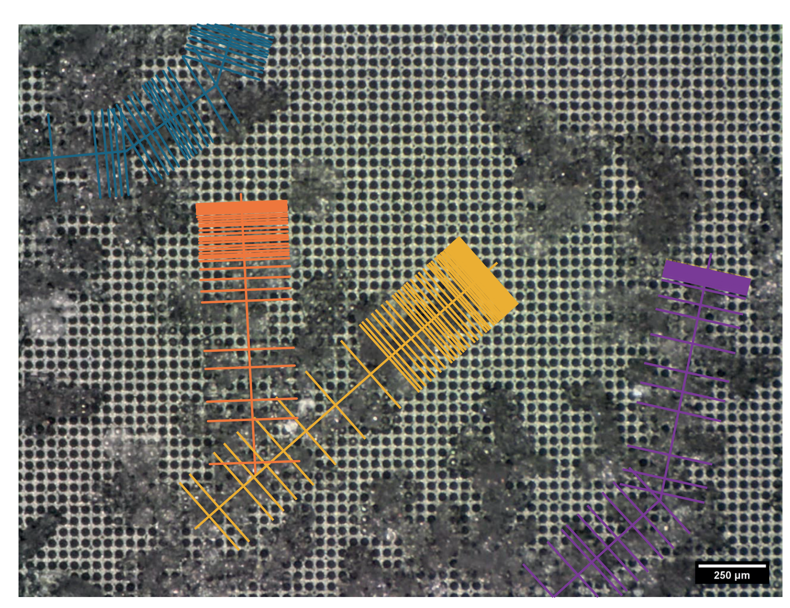
S 2.8

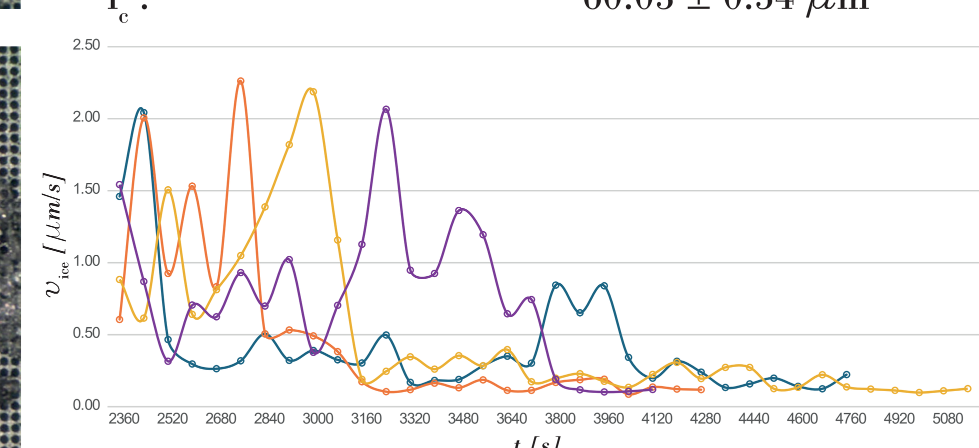




Duration: 00:50:00 to 02:10:00
Ice dendrites speed: 0.35 ± 0.19 μm/s
Droplet Density: 277 ± 5 droplets/mm²
l_c: 60.03 ± 0.54 μm

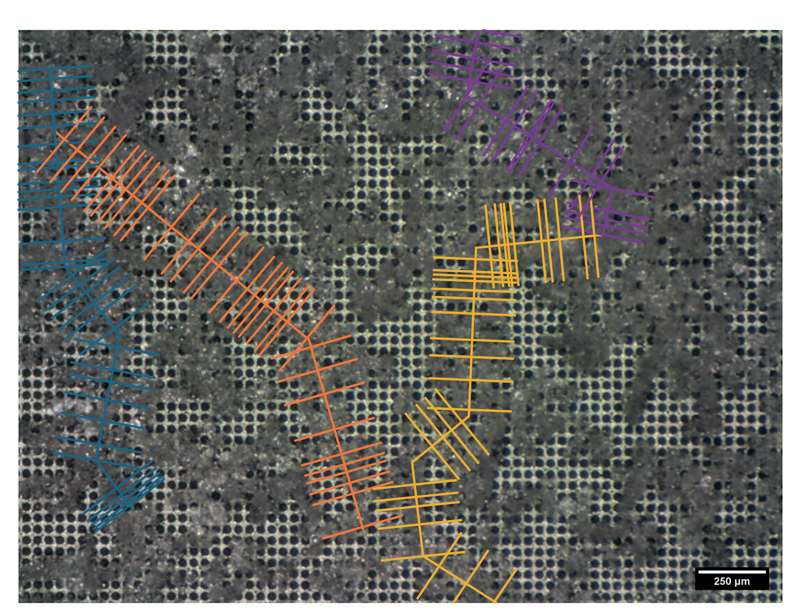
S 4.2

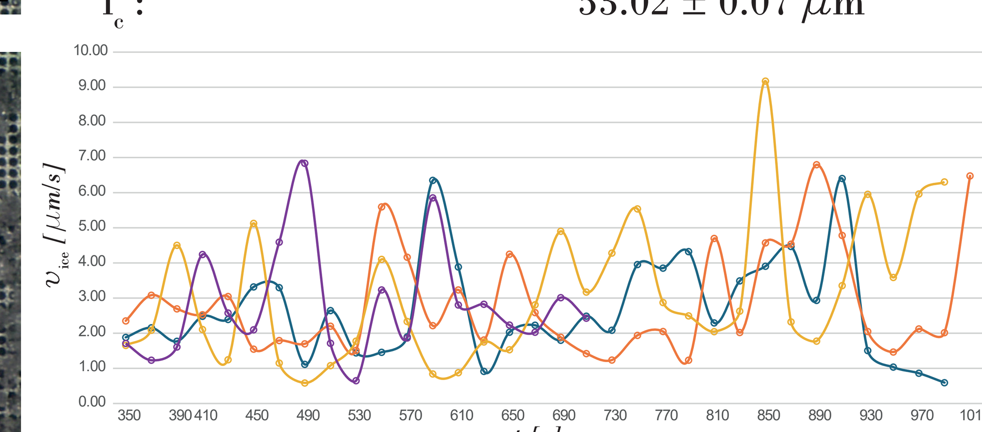




Duration: 00:38:00 to 01:28:00
Ice dendrites speed: 0.54 ± 0.15 μm/s
Droplet Density: 356 ± 1 droplets/mm²
l_c: 53.02 ± 0.07 μm

S 8.4

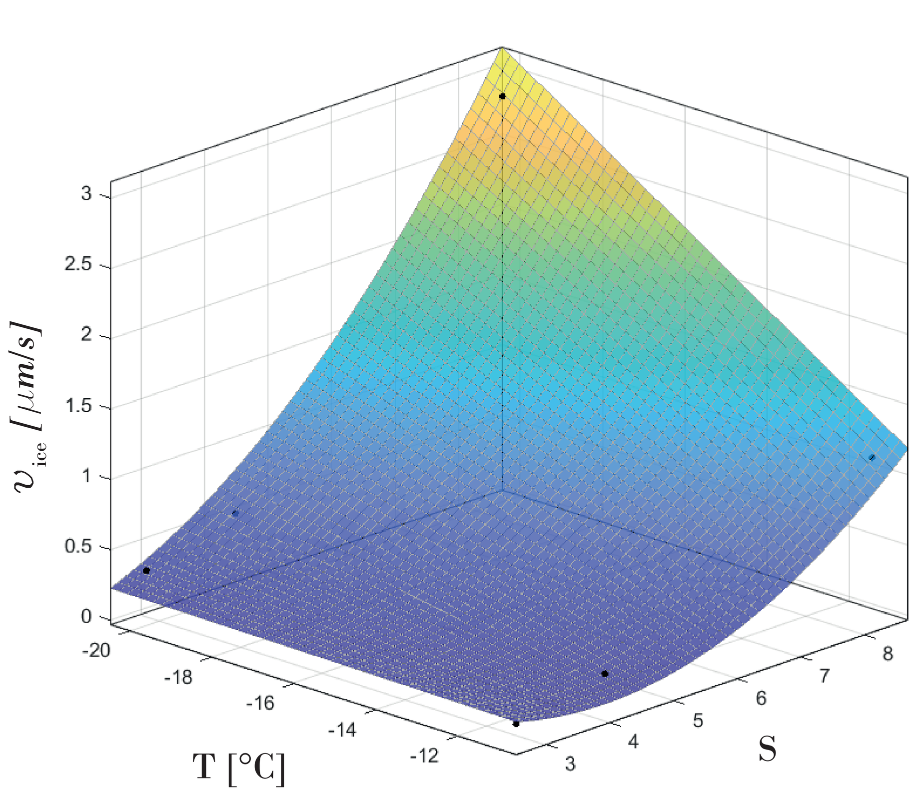




Duration: 00:05:30 to 00:24:00
Ice dendrites speed: 2.85 ± 0.18 μm/s
Droplet Density: 574 ± 4 droplets/mm²
l_c: 41.72 ± 0.15 μm

Results

Ice Dendrites Speed

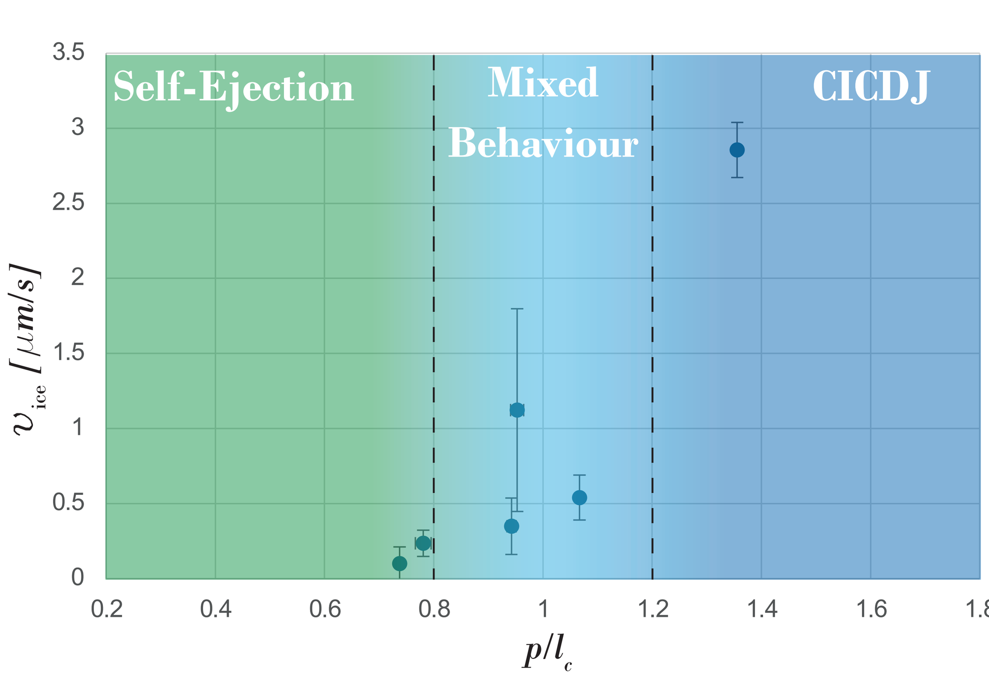


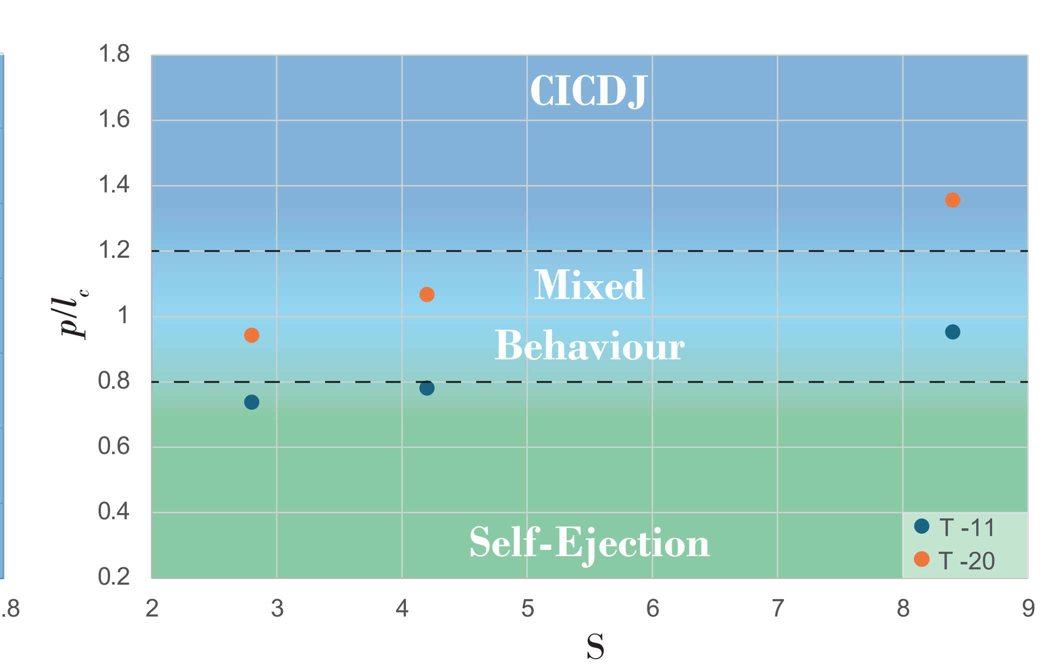
The ice propagation speed v_{ice} increases with higher supersaturation ratio (*S*) and decreasing temperatures, due to the success of ice-bridging events. An increase in nucleation density decreases the distance between droplets, which can be estimated with the following formula:

$$l_c \cong \sqrt{1/\rho_c}$$

When $l_c \approx$ unit cell size (p), an intermediate behavior between CIDJ and self-ejections is observed, marking the regime change.

Nucleated Droplet Density





From the analyses conducted, it is evident that the optimal design consists of a structure composed of nanostructured microcones. The best performance in terms of Self-Ejection events is achieved when the unit cell defined by the pitch *p* is as small as possible.

References

[1] N. G. Di Novo, A. Bagolini, N. M. Pugno. Single Condensation Droplet Self-Ejection from Divergent Structures with Uniform Wettability. ACS Nano 2024 18 (12), 8626-8640.

[2] N. G. Di Novo, A. Bagolini, N. M. Pugno. Ice-Bridging Frustration by Self-Ejection of Single Droplets Results in Superior Anti-Frosting Surfaces. Adv. Mater. Interfaces 2024, 11, 2300759.