THERMAL & FLUIDS ANALYSIS WORKSHOP
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Development of a Novel Direct-to-Chip Evaporator using Hollow Micropillars for Thermal Management in High Heat Flux Applications

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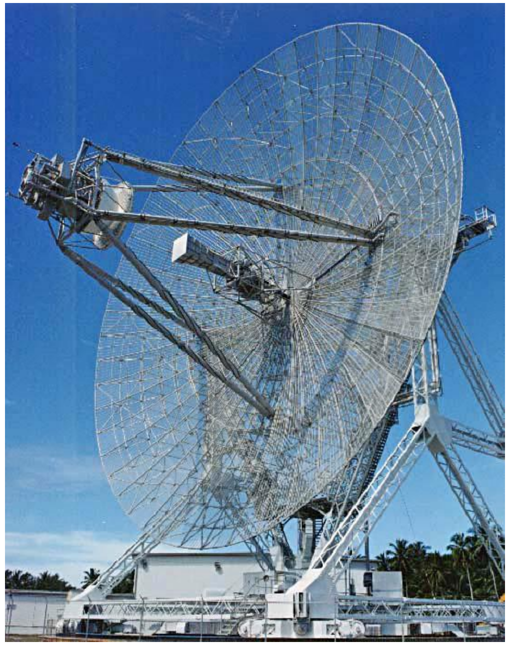
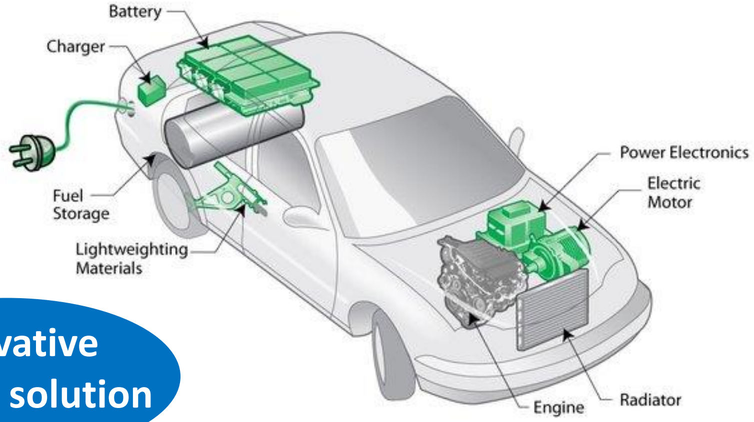
Outline

Introduction

- Tremendous growth in power electronics and microprocessors.
- Led to the improvements in technology across defense, commercial, and space applications.
- As the performance and size reduces, the heat generated increased significantly
- High heat flux generated by these devices limit their performance

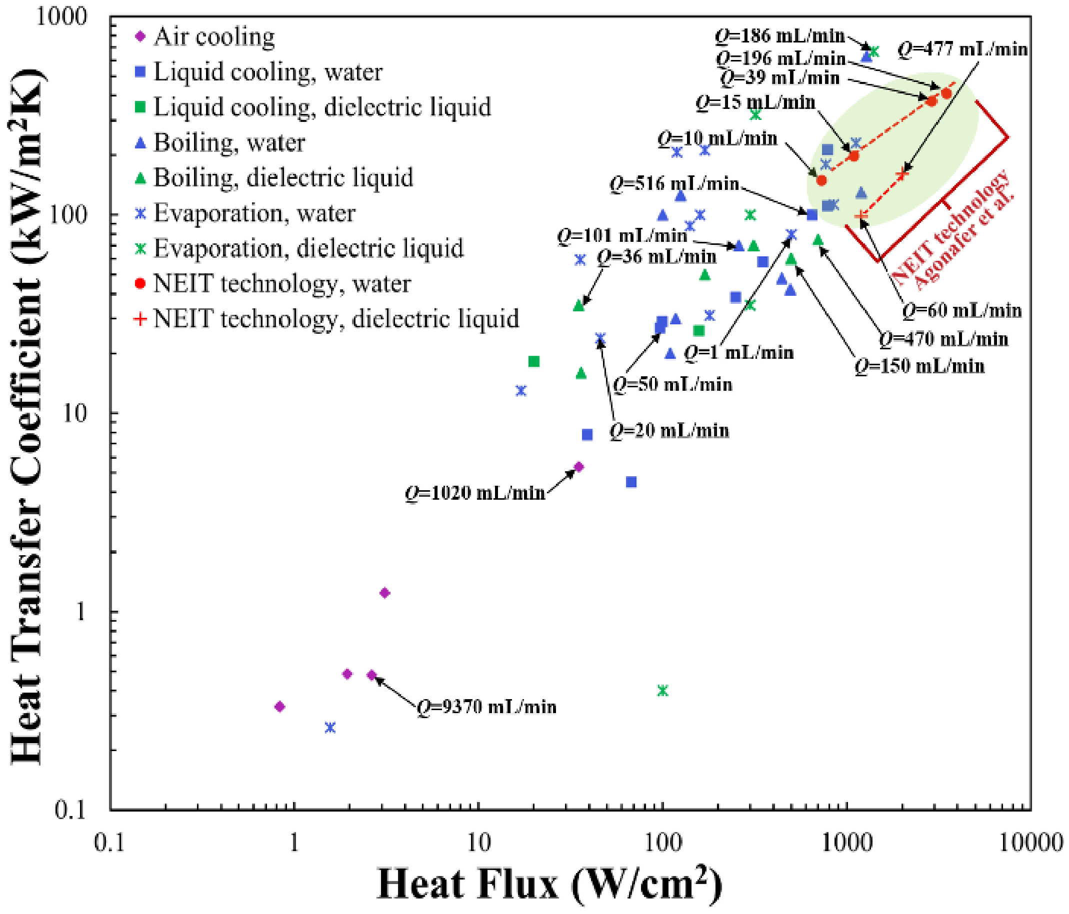




- Size reduction
- Performance increase
- Cost reduction

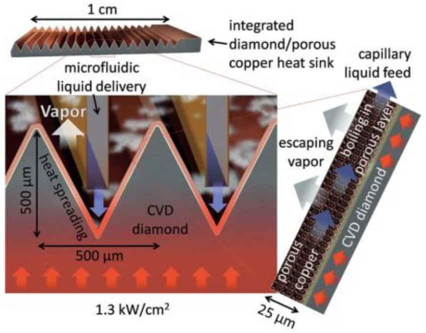
→ Increased heat energy → Innovative thermal solution

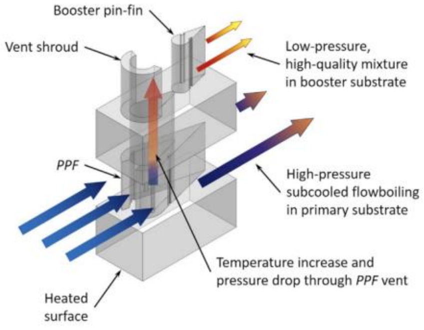
- Thermal management to remove excess energy to improve reliability and prevent premature failure
- Cooling technologies evolving to accommodate steep increase in heat flux.
- Moving from air cooling to single-phase to multi-phase heat transfer

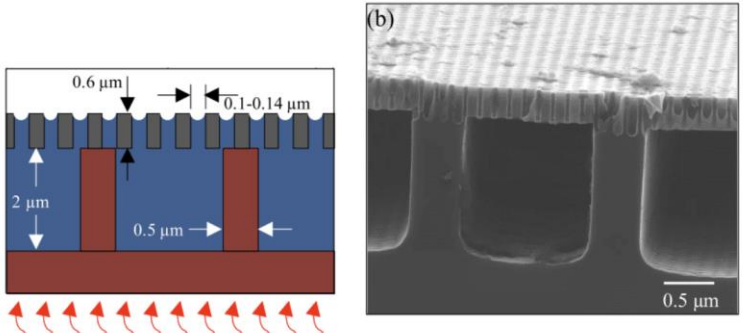


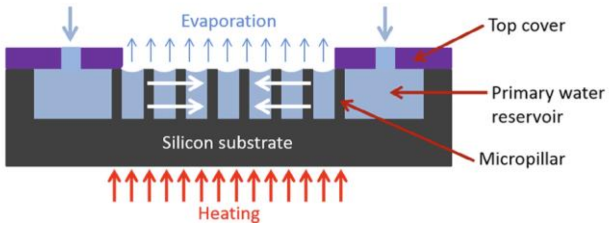
Introduction: State-of-the-art two-phase technologies

Author	Method	Coolant	Heat Flux (W/cm^2)	Pumping Power (W)	HTC (W/m^2.K)
Woodcock et al.	Flow Boiling - piranha pin-fins	HFE-7000	700	0.94	7.5×10^4
Palko et al.	Flow Boiling - diamond microchannels with microporous copper.	Water	1280	0.133	6.3×10^4
Adera et al.	Capillary Thin-film evaporation - micropillar wicks	Water	36	-	5.6×10^5
Hanks et al.	**Capillary thin-film evaporation - nanoporous membrane**	**Pentane**	**1400**	**-**	$\mathbf{6.6 \times 10^5}$





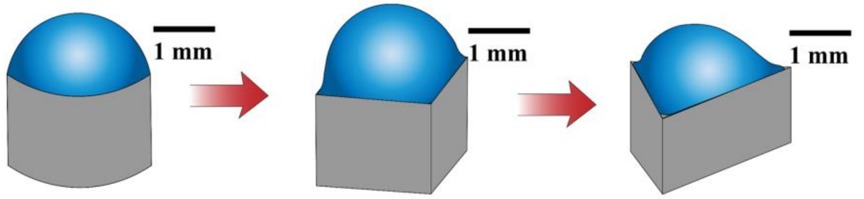


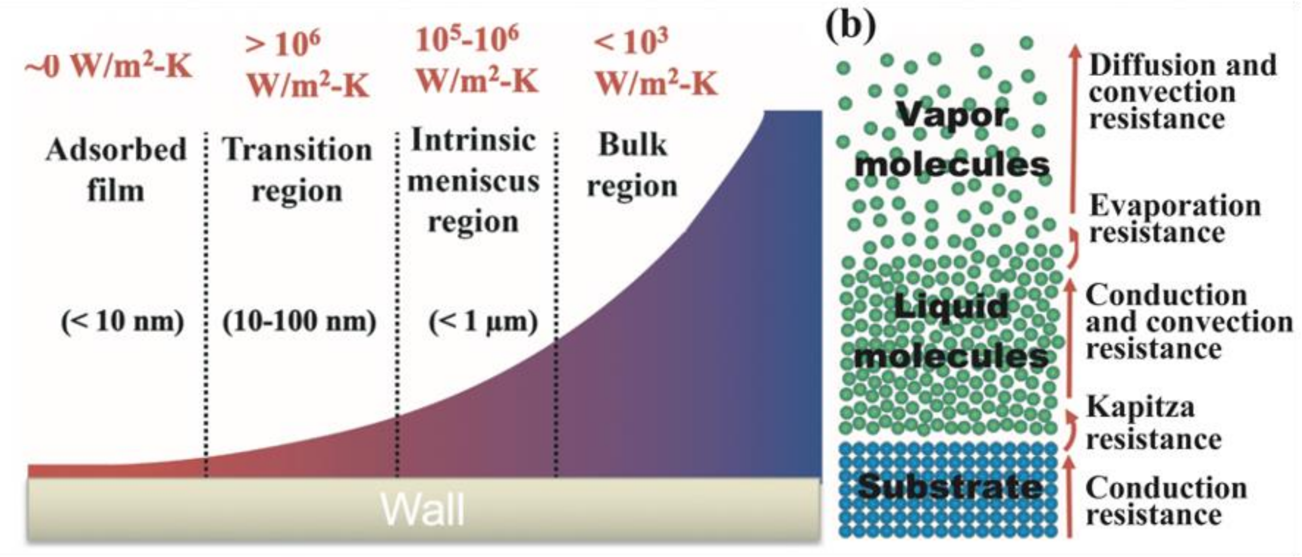


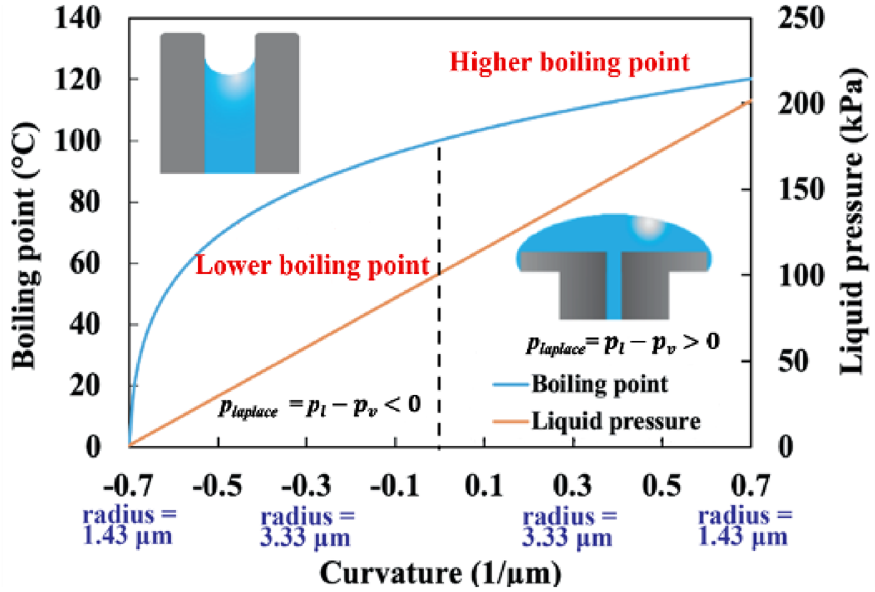
How do we scale these technologies for high-powered electronics?

- Different meniscus regions give different evaporation performance during evaporation
- Liquid pressure reduced for a concave meniscus lowering the boiling point
- Convex meniscus reduces early risk of boiling.
- Traditionally, a concave meniscus is used extend the transition region
- Expanded transition region by introducing asymmetric droplets which increase the perimeter-to-area ratio

Micropillar shape effect

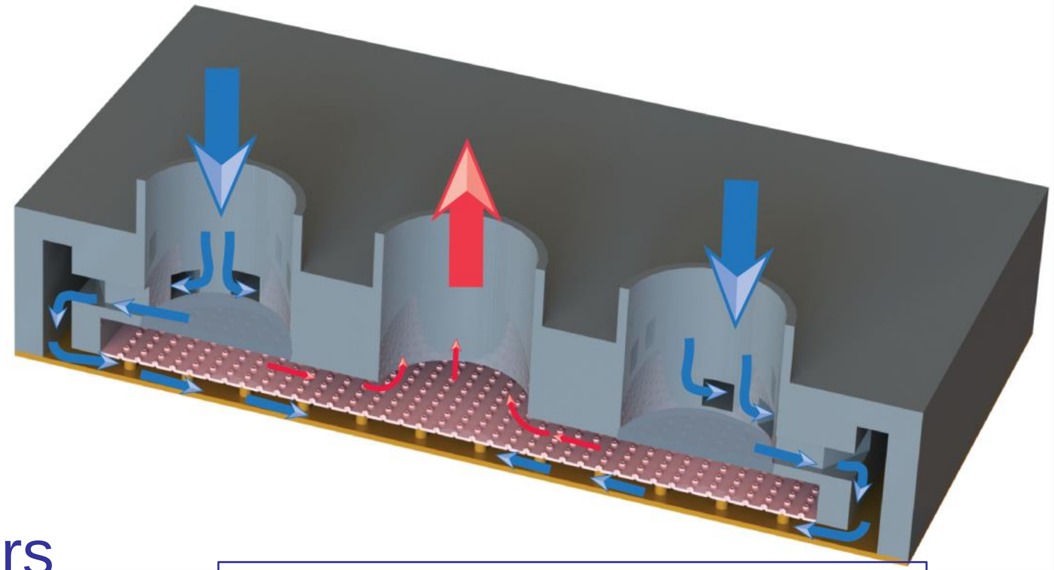




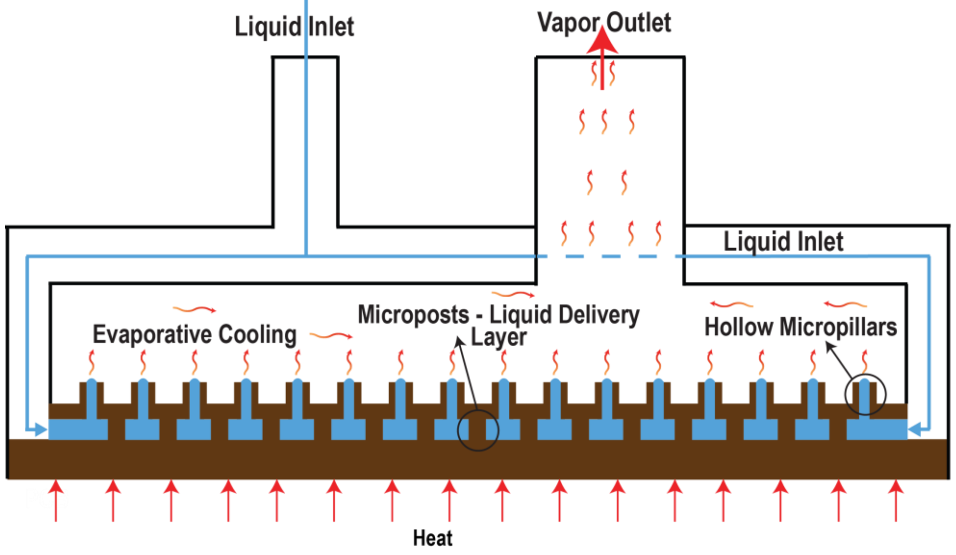


Design of pumped microdroplet evaporation

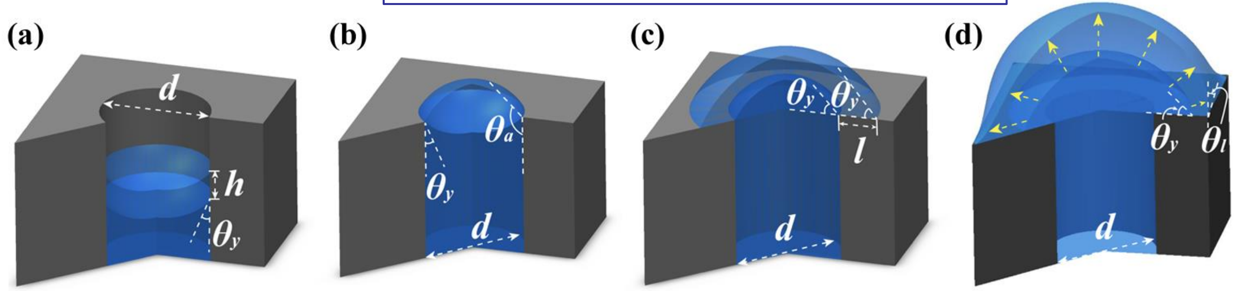
- Evaporative system consists of
  - Evaporator: arrays of hollow micropillars
  - Liquid delivery system (LDL): arrays of solid micropillars
- Liquid delivered through liquid inlets
- Delivered to the LDL through four directions
- Coolants suspended atop of hollow micropillars



Cross-sectional view of the evaporative system

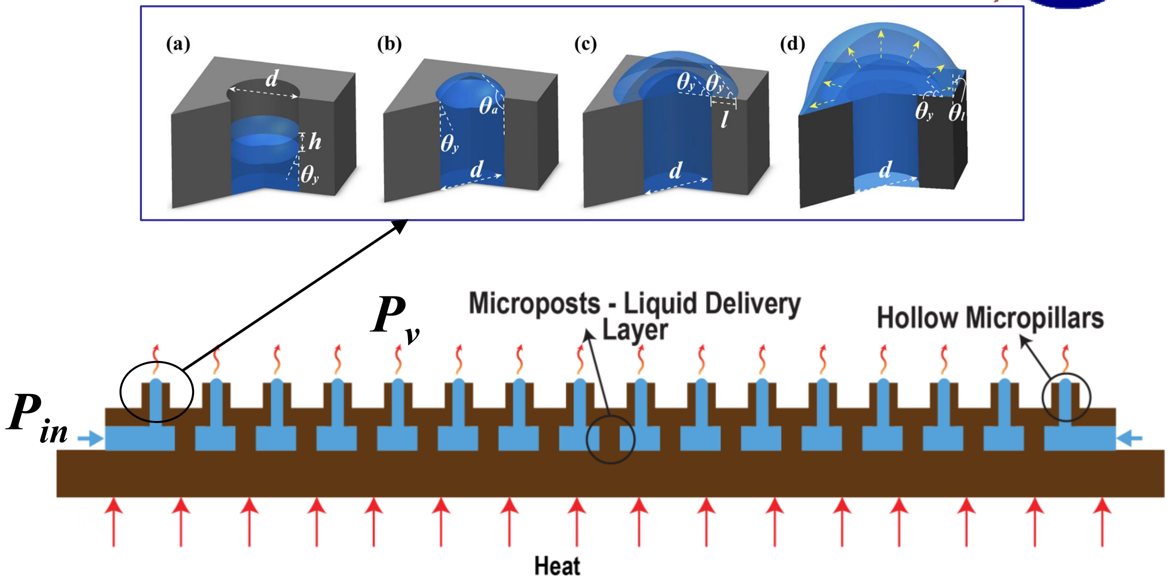


Different stages of wicking



Wicking → Pivoting → Advancing → Pinning

- To understand the system behavior, pressure analysis conducted
- Based on the working condition liquid pressure changes
- Suppress nucleation by pressurizing the system



$$P_{in} = P_{laplace} + \Delta P_{LDL} + \Delta P_{por}$$
$$P_{laplace} = P_l - P_v$$

$$\Delta p_{wicking} = -\frac{4\gamma_{la}\cos\theta_y}{d}$$

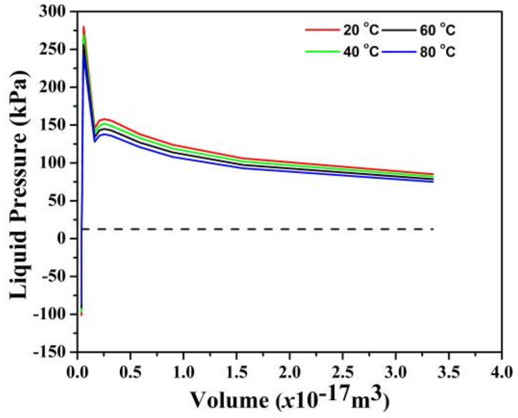
$$\Delta p_{pivoting} = -\frac{4\gamma_{la}\cos\theta_a}{d}$$

$$\Delta p_{expanding} = \frac{4\sin\theta_y}{d+2l}$$

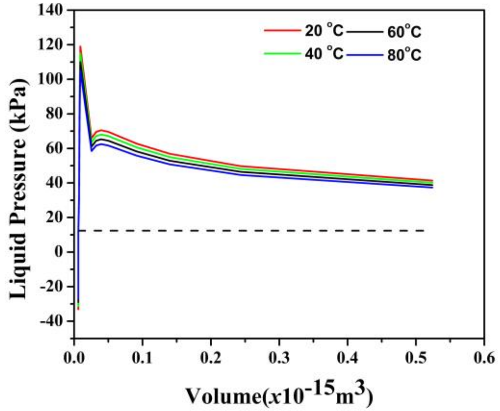
Modeling cont….

- Liquid pressure for water considering a vapor pressure at T_{sat} = 50 ^{o}C
- At pillar hole diameter of 2 um liquid can be pressurized up to 300kPa

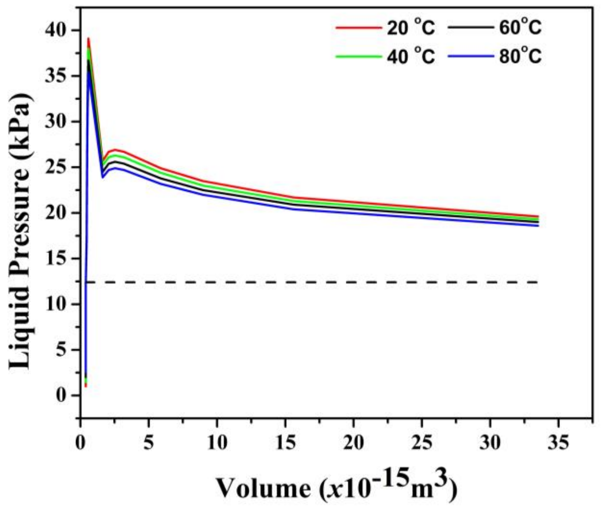
2 um



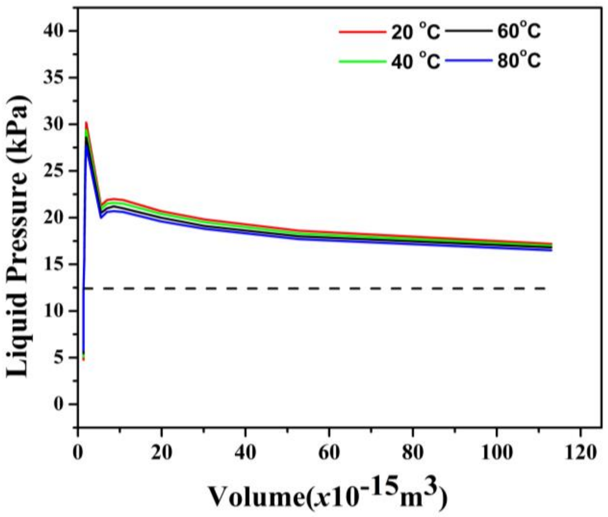
5 um



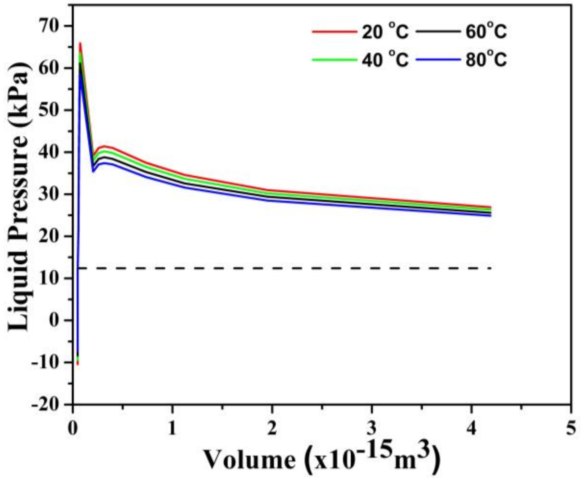
30 um



20 um

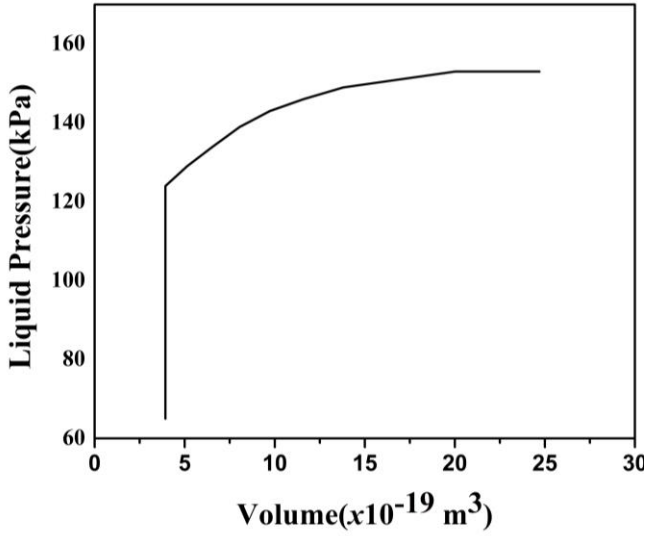


10 um

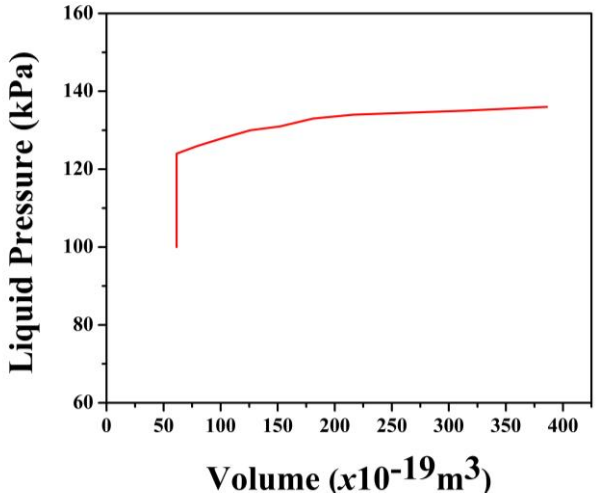


- Liquid pressure for R245fa considering a vapor pressure at T_{sat} = 20 ^{o}C
- Low surface tension has higher liquid pressure at the outer edge
- Pressurize the system up to 160 kPa for 2um hollow pillar

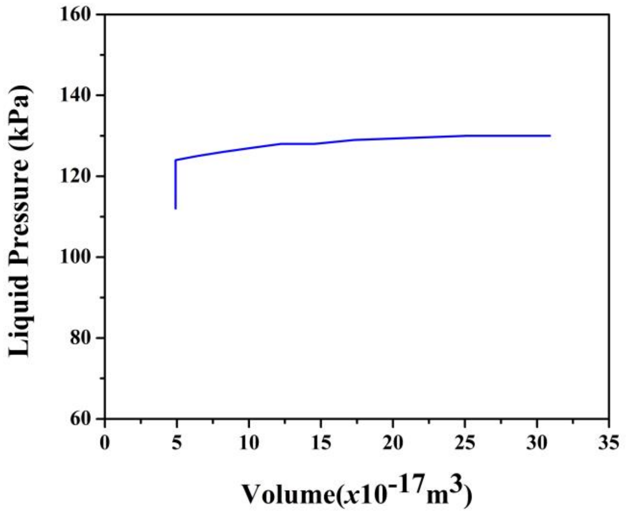
2 um



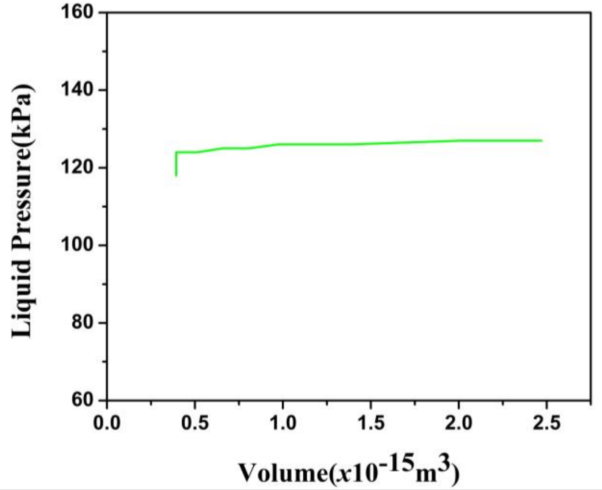
5 um



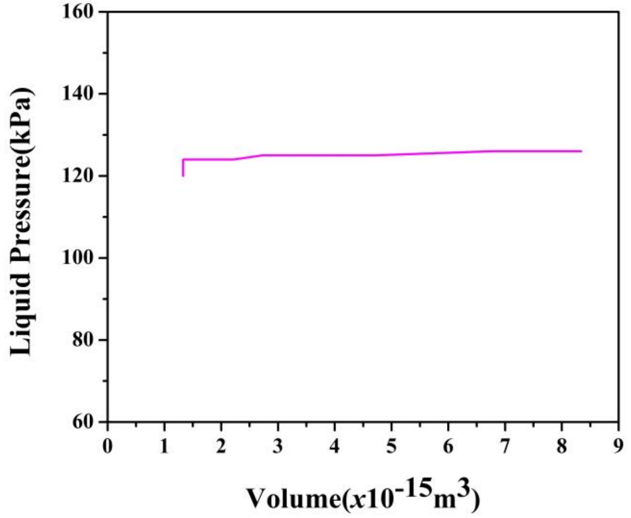
10 um



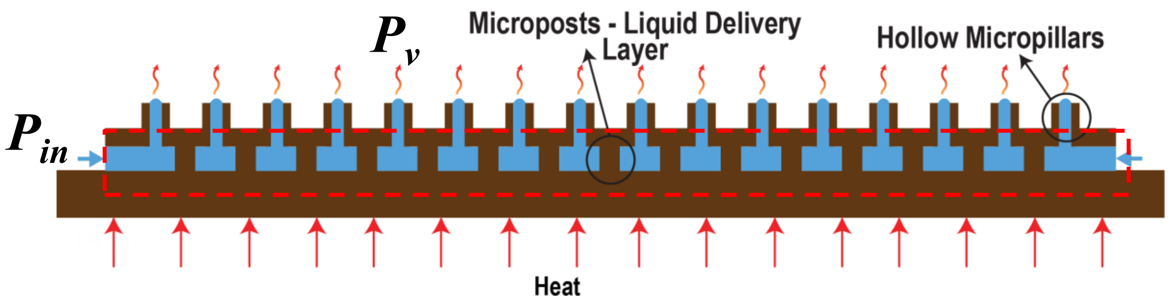
20 um



30 um



- LDL design need to include
  - Low pressure drop
  - Low thermal resistance
  - Minimize evaporator hole's blockage



D[um]	Height[um]	pitch [um]	ΔP [Pa]	dT [C]
50	50	50	2.87E+04	5.06
50	50	100	5.96E+03	11.06
50	50	150	2.35E+03	18.93
50	40	50	3.58E+04	4.05
50	40	100	7.45E+03	8.85
50	40	150	2.94E+03	15.15
50	30	50	4.78E+04	3.03
50	30	100	9.93E+03	6.63
50	30	150	3.92E+03	11.36

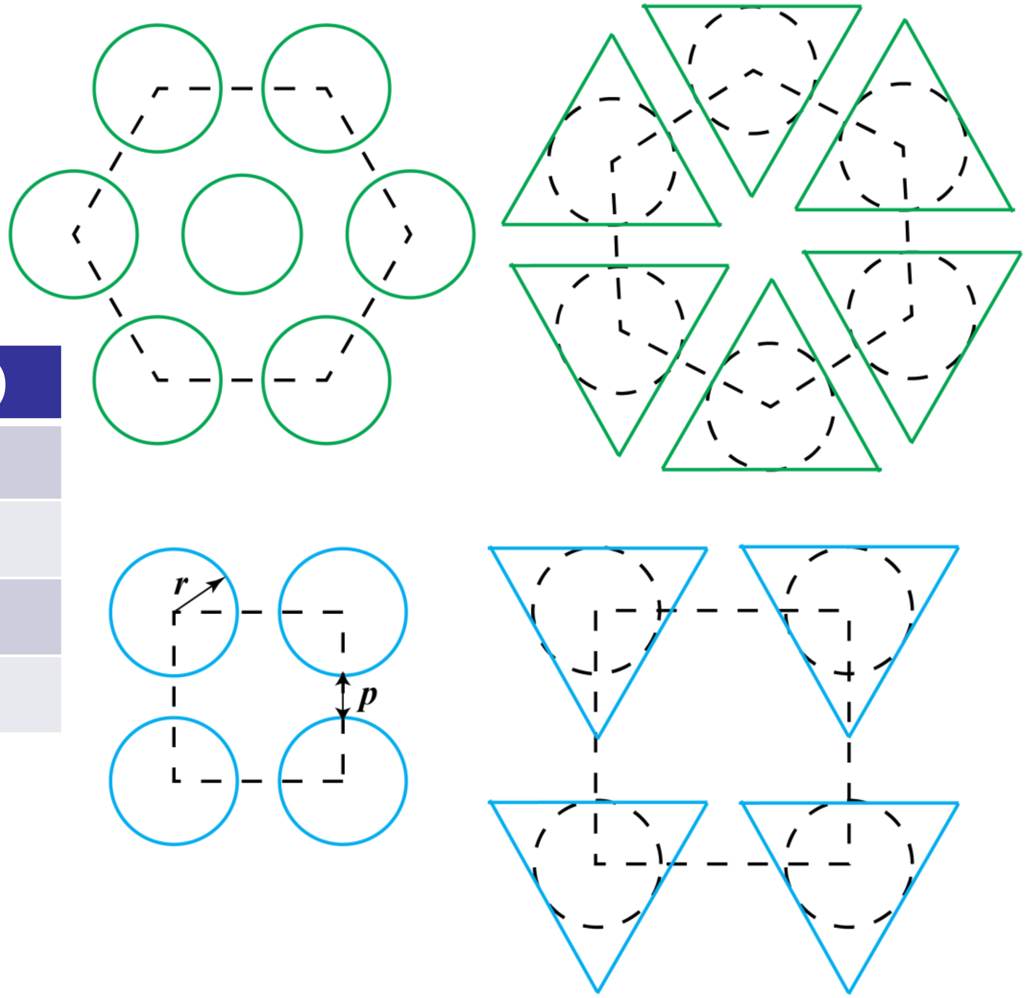
Modeling cont….

- To understand the thermal performance of the evaporator numerical analysis is conducted
- Different parameters affect the performance of the evaporator
  - Droplet size
  - Interpillar distance (packing density)
  - Arrangements
  - Shape of the pillar
  - Wicking stage of the droplet
  - Substrate thickness
  - Material property of the substrate
  - Coolants

Micropillar arrangement

- Calculate the pillar coverage
  - different arrangements and
  - Pillar's shape

Shapes	Arrangement	r (um)	p (um)	Pillar coverage (%)
Circular	Hexagonal	10	5	58.04
	Rectangular	10	5	50.27
Triangular	Hexagonal	10	5	64
	Rectangular	10	5	42.56



- To reduce computational cost the LDL and evaporator are separated
- The droplet assumed to be at steady state

Liquid domain: $\nabla.\vec{V}=0$

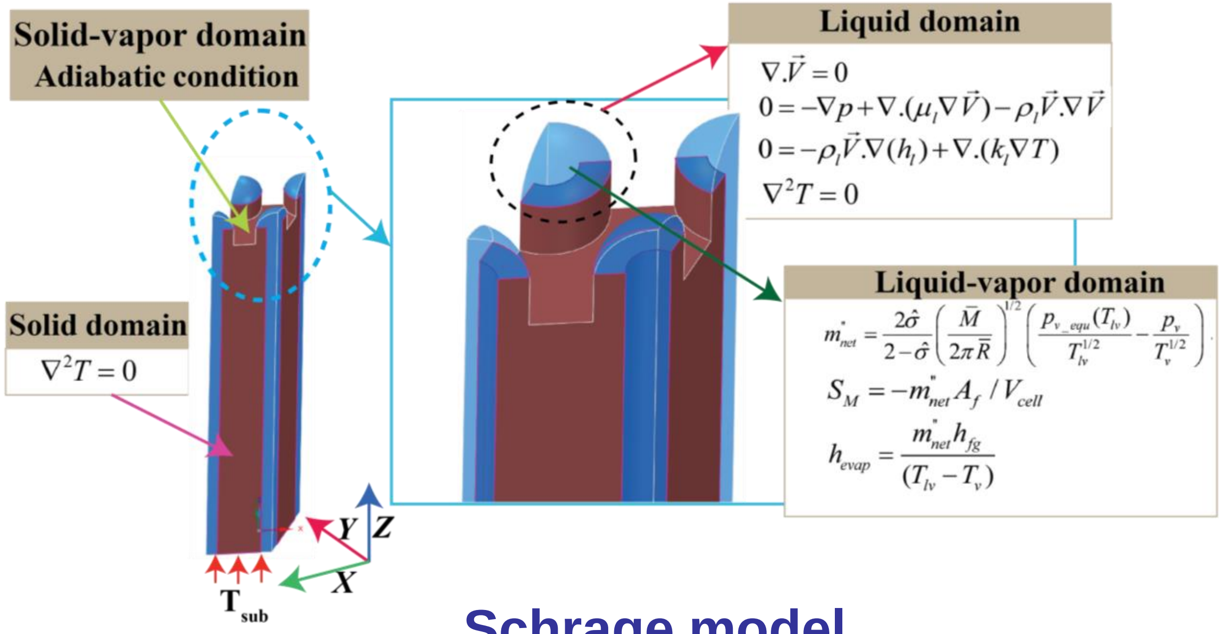
$$0=-\nabla p+\nabla.(\mu_l \nabla \vec{V})-\rho_l \vec{V}.\nabla \vec{V}$$

$$0=-\rho_l \vec{V}.\nabla(h_l)+\nabla.(k_l \nabla T).$$

Solid domain: $\nabla^2 T=0.$

Liquid- vapor interface: $S_M=-m''_{net} A_f / V_{cell}$

$$h_{evap}=\frac{m''_{net} h_{fg}}{(T_{lv}-T_v)}.$$



Schrage model

$$m''_{net}=\frac{2\hat{\sigma}}{2-\hat{\sigma}}\left(\frac{\bar{M}}{2\pi \bar{R}}\right)^{1/2}\left(\frac{p_{v\_equ}(T_{lv})}{T_{lv}^{1/2}}-\frac{p_v}{T_v^{1/2}}\right)$$

$$p_{v\_equ}(T_{lv})=p_{sat}(T_{lv})$$

$$p_{sat}(T_{lv})=p_{sat\_ref}\exp\left(\frac{\bar{M}h_{fg}}{\bar{R}}\left(\frac{1}{T_{sat\_ref}}-\frac{1}{T_{lv}}\right)\right).$$

Results and Discussion

- Effects of inner/outer droplet

parameter	shape	T [C]	Pitch	heat flux
outer	circular	70	3	386.27
inner	circular	70	3	131.28

- Effects of accommodation coefficient

parameter	shape	T [C]	AC	heat flux
AC	circular	70	1	386.27
	circular	70	0.3	323.11

- Effects of substrate thickness

Results and Discussion

- Effects of substrate thickness

parameter	shape	T [C]	Thickness [um]	heat flux [W/cm^2]
Substrate thickness	circular	70	200	386.27
	circular	70	100	462.23

- Effects of shapes

parameter	shape	T [C]	AC	heat flux [W/cm^2]
Shapes	circular	70	1	386.27
	Triangular	70	1	438.42

Conclusion

- Increase the liquid pressure using surface physics
- Hollow micropillars based droplets evaporation dissipate high heat fluxes
- Improve the suppression of nucleate boiling
- Extend the saturation pressure using positive LaPlace pressure created by droplets
- The hollow micropillar droplets-based evaporator address the reliability issues caused by flooding in passive systems

Future Work

- Conduct experimental study to validate the simulation work
  - For different working conditions
  - For different coolants
  - Substrate materials
- Develop a control feedback loop to further improve any flooding problems
- Experimentally show the effect of surface treatment on the improvement in holding higher pressure

References

- [1] M. M. Nahar, B. Ma, K. Guye, Q. H. Chau, J. Padilla, M. Iyengar, D. Agonafer, Microscale evaporative cooling technologies for high heat flux microelectronics devices: Background and recentadvances, Applied Thermal Engineering (2021) 117109.
- [2] A. Bar-Cohen, F. L. Robinson, D. C. Deisenroth, Challenges and opportunities in gen3 embeddedcooling with high-quality microgap flow, in: 2018 International Conference on Electronics Packagingand iMAPS All Asia Conference (ICEP-IAAC), IEEE, 2018, pp. K–1.
- [3] L. Shan, S. Shuai, B. Ma, Z. Du, B. Dogruoz, D. Agonafer, Numerical investigation of shape effecton microdroplet evaporation, Journal of Electronic Packaging 141 (4) (2019)
- [4] J. Li, L. Shan, B. Ma, X. Jiang, A. Solomon, M. Iyengar, J. Padilla, D. Agonafer, Investigation ofthe confinement effect on the evaporation behavior of a droplet pinned on a micropillar structure,Journal of colloid and interface science 555 (2019) 583–594.
- [5] L. Shan, J. Li, B. Ma, X. Jiang, B. Dogruoz, D. Agonafer, Experimental investigation of evaporationfrom asymmetric microdroplets confined on heated micropillar structures, Experimental Thermaland Fluid Science 109 (2019) 109889.
- [6] L. Shan, B. Ma, J. Li, B. Dogruoz, D. Agonafer, Investigation of the evaporation heat transfermechanism of a non-axisymmetric droplet confined on a heated micropillar structure, Internationaljournal of heat and mass transfer 141 (2019) 191–203.

Acknowledgement

All NEIT Lab team members

Back up slides

Parameters	Values
Droplet size	5-30 um
pitch	3um
shape	circular, triangular
wicking stage	inside/outside hole
substrate thickness	100/200 um
Substrate material	silicon, copper
Coolants	water