Zhengmao Lu

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Education

Ph.D. in Mechanical Engineering, Minor in Quantum Information, MIT 6/2018

M.S. in Mechanical Engineering, MIT 9/2014

B.S. in Mechanical Engineering, Tsinghua University, Beijing 7/2012

Research Experience

Postdoctoral Researcher Advisor: Prof. Jeffrey Grossman, MIT 10/2018-present

Developed a robust and low-cost filtration membrane based on coal-derived graphene oxide

Established a transport-based model for bubble nucleation on gas evolving electrodes

Invented a hybrid thermal management scheme integrating evaporative cooling and radiative cooling

Designed an evaporation-insulation bilayer as a packaging material with extended cooling time

Developed a thin film flexible stretch sensor based on natural carbon materials

Graduate Researcher Advisor: Prof. Evelyn N. Wang, MIT 9/2012-6/2018

Established a general model framework for evaporation from nanopores

Designed and microfabricated an ultrathin nanoporous membrane to probe interfacial transport

Created a hierarchical evaporator for ultrahigh heat flux dissipation

Discovered and characterized non-axisymmetric contact line behaviors in micro/nanostructures

Undergraduate Researcher Advisor: Prof. Xiongying Ye, Tsinghua University 1/2010-6/2012

Prototyped and characterized a polydimethylsiloxane-based magnetic micropump for drug delivery

Publications

In Preparation and Review

3. Z. Lu*, A. Leroy*, L. Zhang, J. Patil, E.N. Wang, J.C. Grossman, "Hybrid evaporative-radiative cooling architecture for large energy savings in buildings," *Nature Sustainability*, under review. *equal contribution

2. K.L. Wilke*, Y. Song*, Z. Lu, E.N. Wang, "Enhanced Laplace Pressures for Functional Surfaces: Switchability and Selectivity," in preparation. *equal contribution.

1. G. Vaartstra, Z. Lu, J.C. Grossman, E.N. Wang, "Revisiting the Schrage Equation for Engineering Analysis: Validity, Error Quantification, and Alternatives," in preparation.

Journal Articles

34. C.D. Díaz-Marín, L. Zhang, Z. Lu, M. Alshrah, G. Chen, J.C. Grossman, E.N. Wang, "Kinetics of sorption in hygroscopic hydrogels," *Nano Letters*, accepted.

33. K.L. Wilke*, Z. Lu*, Y. Song, E.N. Wang, "Turning traditionally non-wetting surfaces highly wetting to even ultra-high surface energy liquids," *Proceedings of the National Academy of Sciences of the United States of America*, in press. *equal contribution.

32. G. Vaartstra, Z. Lu, J.C. Grossman, E.N. Wang, "Numerical validation of the dusty-gas model for binary diffusion in low aspect ratio capillaries," *Physics of Fluids* (doi: 10.1063/5.0072800). **Featured Article.**

31. L. Zhang, S. Gong, Z. Lu, X. Li, P. Cheng, E.N. Wang, "Boiling crisis due to bubble interactions," *International Journal of Heat and Mass Transfer* 2021 (doi: 10.1039/D0TA08928A).

30. J. Patil, A. Jana, B. Getachew, D. Bergsman, Z. Gariepy, B. Smith, Z. Lu, J.C. Grossman, "Conductive carbonaceous membranes: recent progress and future opportunities," *Journal of Materials Chemistry A* 2021 (doi: 10.1039/D0TA08928A).

29. L. Zhang, R. Iwata, L. Zhao, S. Gong, Z. Lu, Z. Xu, Y. Zhong, J. Zhu, S. Cruz, K.L. Wilke, P. Cheng, E.N. Wang, "A universal framework for nucleation site distribution," *Cell Reports Physical Science* 2020 (doi: 10.1016/j.xcrp.2020.100262). **Media Coverage: MIT News.**

28. L. Zhang, S. Gong, Z. Lu, P. Cheng, E.N. Wang, "A unified relationship between bubble departure frequency and diameter during nucleate pool boiling," *International Journal of Heat and Mass Transfer* 2021 (doi: 10.1016/j.ijheatmasstransfer.2020.120640).

27. Z. Lu, E. Strobach, N. Chen, N. Ferralis, J.C. Grossman, "Passive Sub-Ambient Cooling from a Transparent Evaporation-Insulation Bilayer," *Joule* 2020 (doi: 10.1016/j.joule.2020.10.005). **Media Coverage: MIT News; New Scientist; Popular Mechanics; Smithsonian Magazine; E&E News; BBC Science Focus.**

26. Z. Lu*, L. Zhang*, R. Iwata, E.N. Wang, J.C. Grossman, "Transport-based modeling of bubble nucleation on gas evolving electrodes," *Langmuir* 2020 (doi: 10.1021/acs.langmuir.0c02690). *equal contribution

25. G. Vaartstra, L. Zhang, Z. Lu, J.C. Grossman, E.N. Wang, "Capillary-fed, thin film evaporation devices," *Journal of Applied Physics* 2020 (doi: 10.1063/5.0021674).

24. D.F. Hanks*, Z. Lu*, J. Sircar, I. Kinefuchi, K.R. Bagnall, T.R. Salamon, D. Antao, B. Barabadi, E.N. Wang, "High Heat Flux Evaporation of Low Surface Tension Liquids from Nanoporous Membranes," *ACS Applied Materials & Interfaces* 2020 (doi: 10.1021/acsami.9b20520). *equal contribution

23. X. Zang, C. Jian, S. Ingersoll, Huashan Li, J. J. Adams, Z. Lu, N. Ferralis, J. C. Grossman, "Laser Engineered Heavy Hydrocarbons: Old Materials with New Opportunities," *Science Advances* 2020 (doi: 10.1126/sciadv.aaz5231). **Media Coverage: MIT News; Popular Mechanics.**

22. Z. Lu, I. Kinefuchi, K.L. Wilke, G. Vaartstra, E.N. Wang, "A Unified Relationship for Evaporation Kinetics at Low Mach Numbers," *Nature Communications* 2019 (doi: 10.1038/s41467-019-10209-w). **Media Coverage: MIT News.**

21. X. Zang, C. Jian, T. Zhu, Z. Fan, W. Wang, M. Wei, B. Li, M.F. Diaz, P. Ashby, Z. Lu, Y. Chu, Z. Wang, X. Ding, Y. Xie, J. Chen, J.N. Hohman, M. Sanghadasa, J.C. Grossman, and L. Lin, "Laser-sculptured ultrathin transition metal carbide layers for energy storage and energy harvesting applications," *Nature Communications* 2019 (doi: 10.1038/s41467-019-10999-z).

20. L. Zhang, Z. Lu, Y. Song, B. Bhatia, K.R. Bagnall, E.N. Wang, "Thermal Expansion Coefficient of Monolayer Molybdenum Disulfide Using Micro-Raman Spectroscopy," *Nano Letters* 2019 (doi: 10.1021/acs.nanolett.9b01829).

19. L. Zhang, Z. Xu, Z. Lu, J. Du, E.N. Wang, "Size distribution theory for jumping-droplet condensation", *Applied Physics Letters* 2019 (doi: 10.1063/1.5081053). **Editor's Pick.**

18. G. Vaartstra, Z. Lu, E.N. Wang, "Simultaneous prediction of dryout heat flux and local temperature for thin film evaporation in micropillar wicks," *International Journal of Heat and Mass Transfer* 2019 (doi: 10.1016/j.ijheatmasstransfer.2019.02.074).

17. L. Zhang, J. Zhu, K.L. Wilke, Z. Xu, L. Zhao, Z. Lu, L.L. Goddard, E.N. Wang, "Enhanced Environmental Scanning Electron Microscopy Using Phase Reconstruction and Its Application in Condensation," *ACS Nano* 2019 (doi: 10.1021/acsnano.8b08389).

16. K.L. Wilke, D.J. Preston, Z. Lu, E. N. Wang, "Toward Condensation-Resistant Omniphobic Surfaces," *ACS Nano* 2018 (doi: 10.1021/acsnano.8b05099). **Media Coverage: MIT News.**

15. L. Zhang, Y. Zhu, Z. Lu, L. Zhao, K.R. Bagnall, S.R. Rao, E.N. Wang, "Characterization of thin film evaporation in micropillar wicks using micro-Raman spectroscopy," *Applied Physics Letters* 2018 (doi: 10.1063/1.5048837).

14. S. Somasundaram, Y. Zhu, Z. Lu, S. Adera, H. Bin, W. Mengyao, C.S. Tan, E.N. Wang, "Thermal design optimization of evaporator micropillar wicks," *International Journal of Thermal Sciences* 2018 (doi: 10.1016/j.ijthermalsci.2018.07.036).

13. D.J. Preston, K.L. Wilke*, Z. Lu*, S.S. Cruz, Y. Zhao, L.L. Becerra, E.N. Wang, "Gravitationally-Driven Wicking for Enhanced Condensation Heat Transfer," *Langmuir* 2018 (doi: 10.1021/acs.langmuir.7b04203). *equal contribution

12. D.F. Hanks, Z. Lu, J. Sircar, T.R. Salamon, D.S. Antao, K.R. Bagnall, B. Barabadi, E.N. Wang, "Nanoporous membrane device for ultra high heat flux thermal management," *Microsystems & Nanoengineering* 2018 (doi: 10.1038/s41378-018-0004-7). **Outstanding Paper**

11. D.J. Preston, Z. Lu, Y. Song, Y. Zhao, K.L. Wilke, D.S. Antao, M. Louis, E.N. Wang, "Heat Transfer Enhancement During Water and Hydrocarbon Condensation on Lubricant Infused Surfaces," *Scientific Reports* 2018 (doi: 10.1038/s41598-017-18955-x). **Top 100 in Materials Science**

10. Y. Zhao, D.J. Preston, Z. Lu, L. Zhang, J. Queeney, E.N. Wang, "Effects of millimetric geometric features on dropwise condensation under different vapor conditions," *International Journal of Heat and Mass Transfer* 2018 (doi: 10.1016/j.ijheatmasstransfer.2017.11.139).

9. Z. Lu, K.L. Wilke, D.J. Preston, I. Kinefuchi, E. Chang-Davidson, E.N. Wang, "An Ultrathin Nanoporous Membrane Evaporator," *Nano Letters* 2017 (doi: 10.1021/acs.nanolett.7b02889).

8. D.J. Preston, Y. Song, Z. Lu, D.S. Antao, E.N. Wang, "Design of lubricant infused surfaces," *ACS Applied Materials & Interfaces* 2017 (doi: 10.1021/acsami.7b14311).

7. K.L. Wilke, B. Barabadi, Z. Lu, T. Zhang, E.N. Wang, "Parametric study of thin film evaporation from nanoporous membranes," *Applied Physics Letters* 2017 (doi: 10.1063/1.4997945).

6. Z. Lu*, D.J. Preston*, D.S. Antao, Y. Zhu, E.N. Wang, "Coexistence of pinning and moving on a contact line," *Langmuir* 2017 (doi: 10.1021/acs.langmuir.7b02070). *equal contribution

5. A. Vega-Flick, R.A. Duncan, J.K. Eliason, J. Cuffe, J.A. Johnson, J.M. Peraud, L. Zeng, Z. Lu, A.A. Maznev, E.N. Wang, J.J. Alvarado-Gil, M. Sledzinska, C.M. Sotomayor Torres, G. Chen, K.A. Nelson, "Thermal transport in suspended silicon membranes measured by laser-induced transient gratings," *AIP Advances* 2016 (doi: 10.1063/1.4968610).

4. Z. Lu, T.R. Salamon, S. Narayanan, K.R. Bagnall, D.F. Hanks, D.S. Antao, B. Barabadi, J. Sircar, M.E. Simon, E.N. Wang, "Design and Modeling of Membrane-Based Evaporative Cooling Devices for Thermal Management of High Heat Fluxes," *IEEE Transactions on Components, Packaging and Manufacturing Technology* 2016 (doi: 10.1109/TCPMT.2016.2576998).

3. Y. Zhu, D.S. Antao, Z. Lu, S. Somasundaram, T. Zhang, E.N. Wang, "Prediction and Characterization of Dry-out Heat Flux in Micropillar Wick Structures," *Langmuir* 2016 (doi: 10.1021/acs.langmuir.5b04502).

2. Z. Lu, S. Narayanan, E.N. Wang, "Modeling of Evaporation from Nanopores with Nonequilibrium and Nonlocal Effects," *Langmuir* 2015 (doi: 10.1021/acs.langmuir.5b01700).

1. M. Du, Z. Lu and X Ye. "Experimental Study on a Small Flux, High Pressure Peristaltic Micropump," *Key Engineering Materials* 2012 (doi: 10.4028/www.scientific.net/KEM.503.354).

Patents

5. Z. Lu, A. Leroy, E.N. Wang, J.C. Grossman, "Hybrid evaporative-radiative cooling panels for efficient air conditioning/refrigeration," provisional application filed.

4. K.L. Wilke, Y. Song, Z. Lu, E.N. Wang, "Omniphilic, Omniphobic, Switchable, and Selective Wetting Surfaces," provisional application filed.

3. G. Vaarstra, E.N. Wang, Z. Lu, K.L. Wilke, L. Zhang, "Area-Enhanced, Hierarchical Evaporator for Extreme Thermal Management," provisional application filed.

2. S.S. Cruz, D.J. Preston, E.N. Wang, K.L. Wilke, Z. Lu, Y. Zhao, L. Becerra, "Wicking condensation assisted by a combination of gravity and suction," in preparation with MIT Technology Licensing Office.

1. K.L. Wilke, D.J. Preston, Z. Lu, E.N. Wang, "Condensation Resistant Omniphobic Reentrant Nanostructures," in preparation with MIT Technology Licensing Office.

Select Conference Proceedings/Presentations

17. Z. Lu, I. Kinefuchi, K.L. Wilke, G. Vaartstra, E.N. Wang, "Kinetically limited evaporation from nanopores," Gordon Research Conference on Micro and Nanoscale Phase Change Heat Transfer, Luca, Italy, February 3-8, 2019.

16. I. Kinefuchi, Z. Lu, H. Matsumoto, H. Imai, T. Hori, Y. Yoshimoto, S. Takagi, E.N. Wang, "Numerical analysis of nonequilibrium gas flows induced by evaporation from two-dimensional nanoscale slit arrays," Annual Meeting of the APS Division of Fluid Dynamics, Atlanta, GA, November 18-20, 2018.

15. Z. Lu, K.L. Wilke, D.J. Preston, I. Kinefuchi, E.N. Wang, "Evaporation from ultra-thin nanoporous membranes into liquid-moist air systems," International Heat Transfer Conference 16, Beijing, China, August 10-15, 2018.

14. Z. Lu, I. Kinefuchi, K.L. Wilke, and E.N. Wang "Probing the Fundamental Evaporation Limit with a Nanoporous Membrane Device," Hilton Head workshop 2018: A Solid-State Sensors, Actuators and Microsystems Workshop, Hilton Head Island, SC, June 3-7, 2018.

13. D.J. Preston, Y. Song, Z. Lu, D.S. Antao, E.N. Wang, "Design of Lubricant Infused Surfaces," MRS Fall Meeting, Boston, MA, November 26-30, 2017.

12. D.J. Preston, Z. Lu, Y. Song, K.L. Wilke, Y. Zhu, D.S. Antao, E.N. Wang, "Gravitationally-Driven Wicking for Enhanced Condensation Heat Transfer," International Conference on Nanochannels, Microchannels, and Minichannels, Cambridge, MA, August 27-30, 2017. **Best Poster**.

11. J. Sircar, D.F. Hanks, Z. Lu, T.R. Salamon, K.R. Bagnall, S. Narayanan, D.S. Antao, B. Barabadi, E.N. Wang, "High Heat Flux Evaporation from Nanoporous Silicon Membranes," IEEE ITHERM 2016 Conference, Orlando, FL, May 30 - June 2, 2017. **Best Paper**.

10. Z. Lu, D.J. Preston, D.S. Antao, Y. Zhu, E.N. Wang, "Capillary Surface in Micropillar Arrays," APS March Meeting, New Orleans, LA, March 13-17, 2017.

9. D.J. Preston, Z. Lu, Y. Zhao, D.S. Antao, K.L. Wilke, E.N. Wang, "Optimal Design of Slippery Liquid-Infused Porous Surfaces for Enhanced Condensation of Low Surface Tension Fluids," APS March Meeting, New Orleans, LA, March 13-17, 2017.
8. Z. Lu, K.L. Wilke, E.N. Wang, "Evaporation from Ultra-Thin Nanoporous Membrane into Air," Gordon Research Conference on Micro- and Nanoscale Phase Change Heat Transfer, Galveston, TX, Jan. 8-13, 2017.
7. D.F. Hanks, J. Sircar, Z. Lu, D.S. Antao, K.R. Bagnall1, B. Barabadi, T.R. Salamon, E.N. Wang "High heat flux evaporative nanoporous silicon membrane device for advanced thermal management," Hilton Head workshop 2016: A Solid-State Sensors, Actuators and Microsystems Workshop, Hilton Head Island, SC, June 5-9, 2016.
6. Y. Zhu, Z. Lu, D.S. Antao, H. Li, T. Zhang, E.N. Wang, "Model Optimization of Dry-out Heat Flux from Micropillar Wick Structures," IEEE ITHERM 2016 Conference, Las Vegas, NV, June 01-03, 2016. **Outstanding Poster**.
5. D.F. Hanks, Z. Lu, J. Sircar, D. Antao, B. Barabadi, T. Salamon, E. Simon, R. Enright, E.N. Wang, "Evaporation Device with Nanoporous Membrane," International Electronic Packaging Technical Conference and Exhibition, San Francisco, CA, July 6-9, 2015.
4. D.F. Hanks, Z. Lu, J. Sircar, R. Raj, D.S. Antao, S. Narayanan, B. Barabadi, R. Enright, T. Salamon, E. Simon, E.N. Wang, "Microfabricated Nanoporous Membrane-Based Evaporation for High Heat Flux Thermal Management," GOMACTech, St. Louis, MO, May 23-26, 2015.
3. Z. Lu, S. Narayanan and E.N. Wang. "Self-regulation of the liquidvapor interface during evaporation from nanopores," Gordon Research Conference on Micro- and Nanoscale Phase Change Heat Transfer, Galveston, TX, Jan. 11-16, 2015.
2. Z. Lu, S. Narayanan, D.F. Hanks, R. Raj, R. Xiao, D.S. Antao and E. N. Wang. "Modeling of Nanoporous Membranes for High Flux Thin Film Evaporation," International Heat Transfer Conference 15, Kyoto, Japan, August 10-15, 2014.
1. D.F. Hanks, Z. Lu, S. Narayanan, K.R. Bagnall, R. Xiao, R. Raj, R. Enright, E.N. Wang, "Nanoporous Evaporation Device for Advanced Electronics Thermal Management," IEEE ITherm Conference, Orlando, FL, May 27-30, 2014. **Best Paper**.

Grant Experience

"Hybrid evaporative and radiative passive cooling for buildings," Jeffrey C. Grossman (PI), submitted to *Advanced Research Projects Agency-Energy*, 2021.

"Hybrid evaporative and radiative cooling as a passive low-cost high-performance solution for food shelf-life extension," Jeffrey C. Grossman (PI), accepted by *J-WAFS Solutions Grant*, 2021.

"High Performance Area-Enhanced Hierarchical Membrane for Extreme Thermal Management," Evelyn N. Wang (PI), accepted by *Air Force Office of Scientific Research*, 2018.

"Hierarchical Evaporative Cooling for 3D Integrated Circuit Stacks," Evelyn N. Wang (PI), submitted to *Semiconductor Research Corp.*, 2018.

"Energy-Efficient Air-Cooled Condenser with Radiative Cooling Coating," TieJun Zhang (PI), accepted by *Research & Development Petroleum Conference and Exhibition*, 2018.

"Capillary-driven Condensation for Heat Transfer Enhancement in Steam Power Plants," Evelyn Wang (PI) accepted by *Department of Energy*, 2017.

"Thermal Wires Transferring Heat Across Kilometers," Evelyn N. Wang (PI) accepted by *Professor Amar G. Bose Research Grants*, 2017.

"A Micro-Raman Thermography System for High Spatial Resolution Thermal Characterization of Microelectronic Devices and their Thermal Management Solutions," Evelyn N. Wang (PI) accepted by *Office of Naval Research*, 2016.

Startup Business Programs

The Engine Blueprint Program — Spring, 2021

New England Regional I-corps — Summer, 2021

Teaching

Kaufman Teaching Certificate Program, MIT — Spring, 2021

Teaching Assistant 2.51 Intermediate Heat and Mass Transfer, MIT — Fall, 2017

Guest Lecturer 2.51 Intermediate Heat and Mass Transfer, MIT — Fall, 2013

Mentoring

Ningxin Chen, MIT (09/2019 - present, Undergraduate Student)

Geoffrey Vaartstra, MIT (09/2017 - 10/2018, Ph.D. Student)

Alina Dale LaPotin, MIT (06/2018 - 10/2018, Ph.D. Student)

Elizabeth Chang-Davidson, MIT (02/2017 - 06/2017, Undergraduate Student)

Award

Wunsch Foundation Silent Hoist and Crane Award - Outstanding Graduate Research, MIT — 2018

Keck Travel Award in Thermal Sciences, MIT — 2017

Outstanding Graduate Award, Tsinghua University — 2012

National Endeavor Scholarship, Tsinghua University — 2011, 2010

First Prize in Mechanical Innovation Design Competition, Beijing — 2010

National Scholarship, Tsinghua University — 2009

Invited Talk

"Understanding and Tailoring Liquid-Gas Interfacial Transport for Next-Generation Energy and Water Technologies", Rice University Mechanical Engineering Seminar Series, December 2020.

Services

Peer-Review Referee for National Science Review, ACS Nano, Nano Letters, ACS Applied Materials & Interfaces, International Journal of Heat and Mass Transfer, Applied Thermal Engineering, International Journal of Thermal Sciences, Advances in Colloid and Interface Science, Journal of Cleaner Production

Hosted one of the Micro-Nano Seminar Series at MIT

Established the Glove Recycling Program in the Grossman Lab