High-Frequency Sequence Regression and Multimodal Fusion for Nonintrusive Thermal Monitoring

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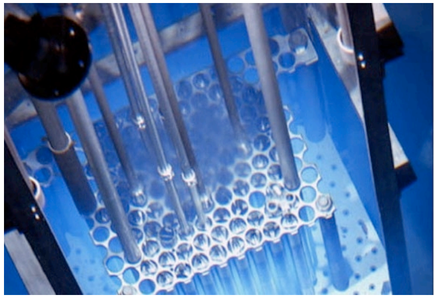
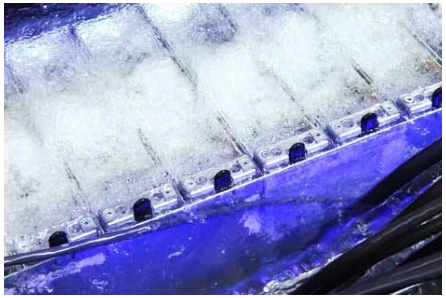
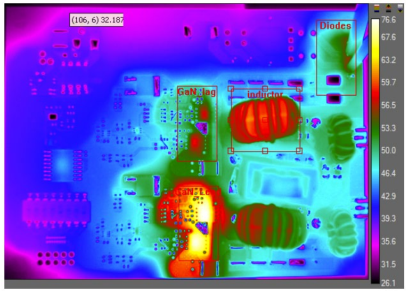
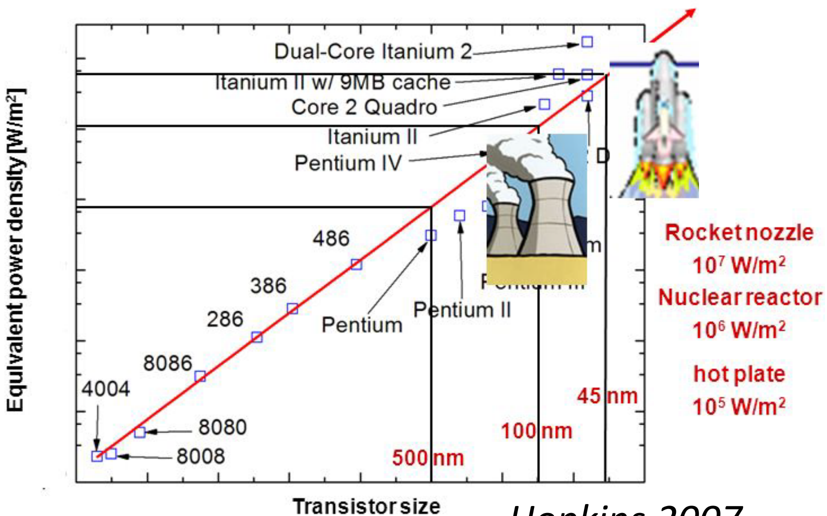
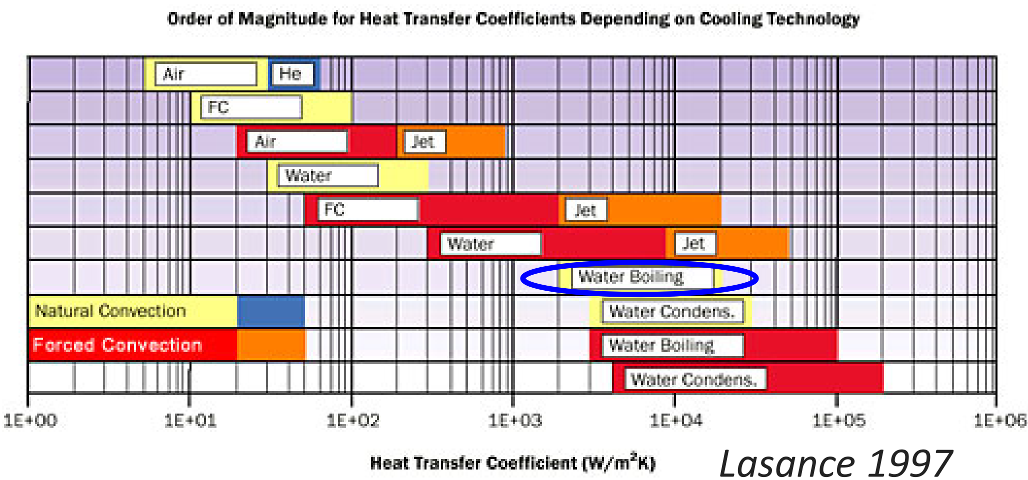
Background: Challenges of Thermal Management

Nuclear Reactor	Concentrated Solar Power and PV	Computer Chips and Data Centers	Wide bandgap Power Electronics
			
Penn State Breazeale Plant	Solana Generating Station	3M (using Intel Chips)	Navitas Power Amplifier



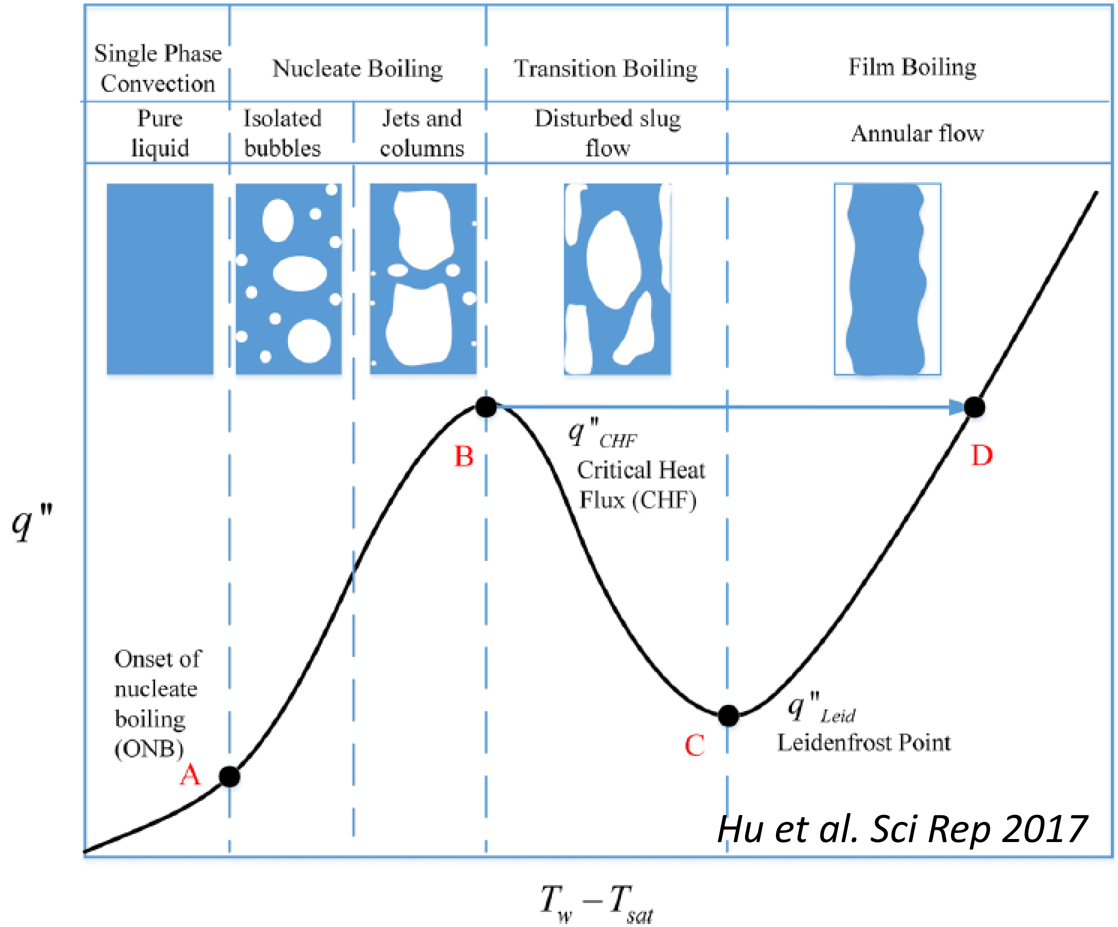
Hopkins 2007



Lasance 1997

Practical Limit of Boiling Heat Transfer

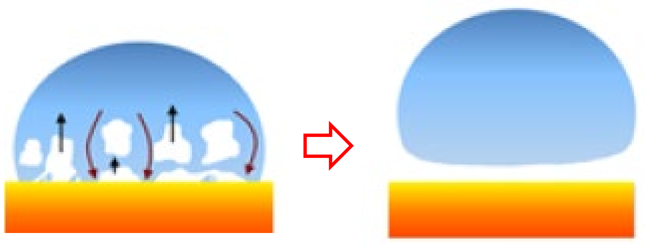
Boiling Regimes in a Representative Boiling Curve



Heat transfer coefficient (HTC): HTC = q" / (T_w – T_{sat})

Critical Heat Flux (CHF): A catastrophic point of failure

Point B: CHF



Nucleate boiling (pre-CHF)

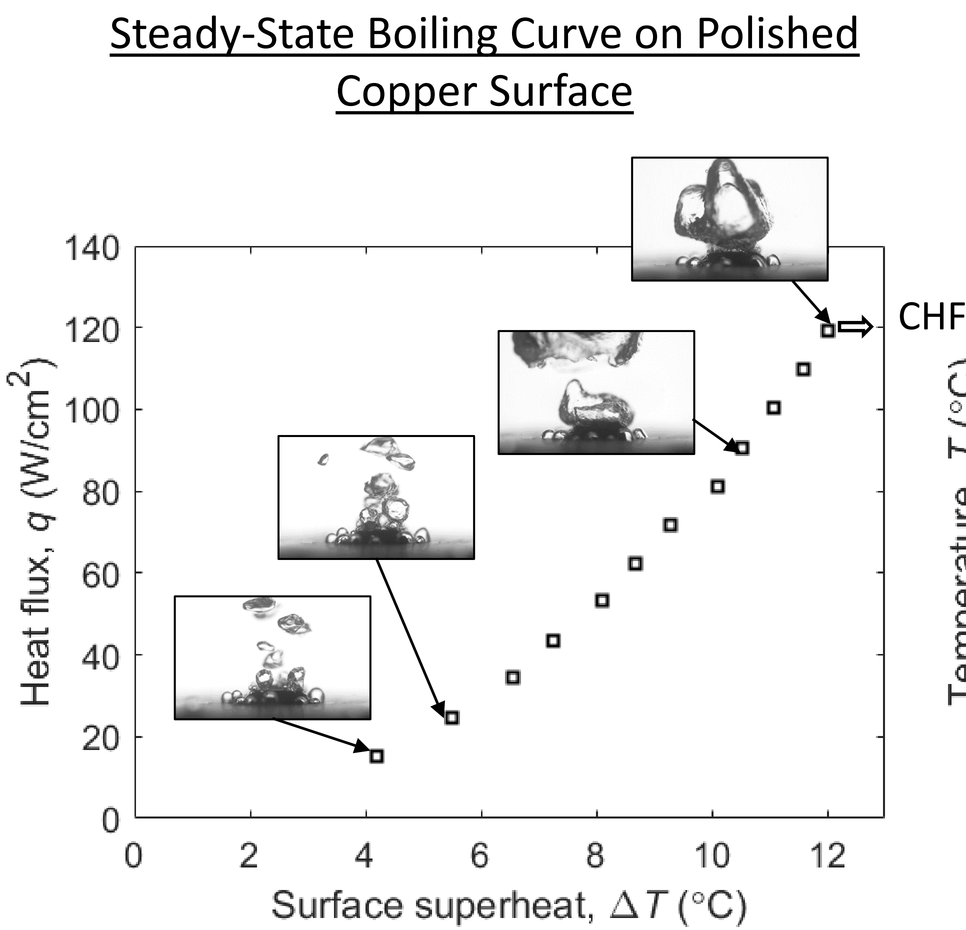
Film boiling (post-CHF)

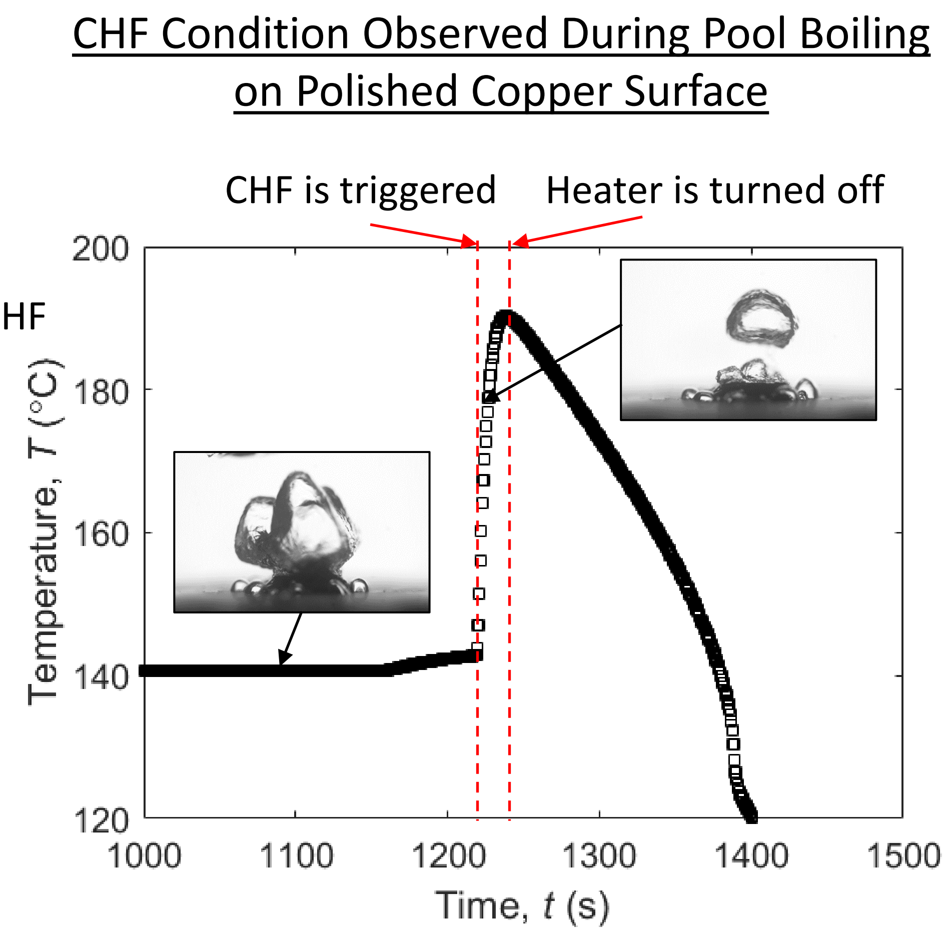
Sheehan et al. UNL

Immediately after CHF is triggered:

- HTC drops by orders of magnitude;
- Surface temperature increases by hundreds of degrees.

Steady-State Boiling Curve and CHF Condition



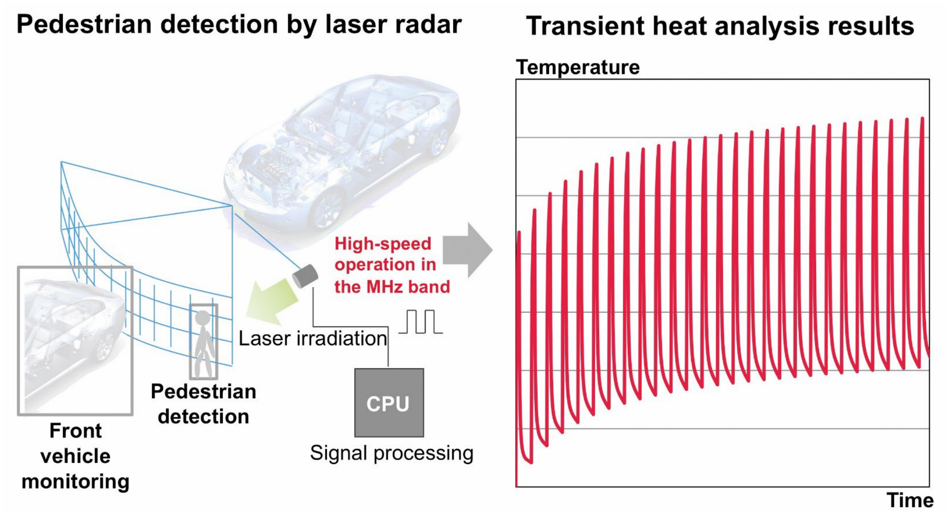


When CHF is triggered, heater temperature increases rapidly (~ 150 ˚C/min).

Thermal Management Challenges Due to Dynamic Loads

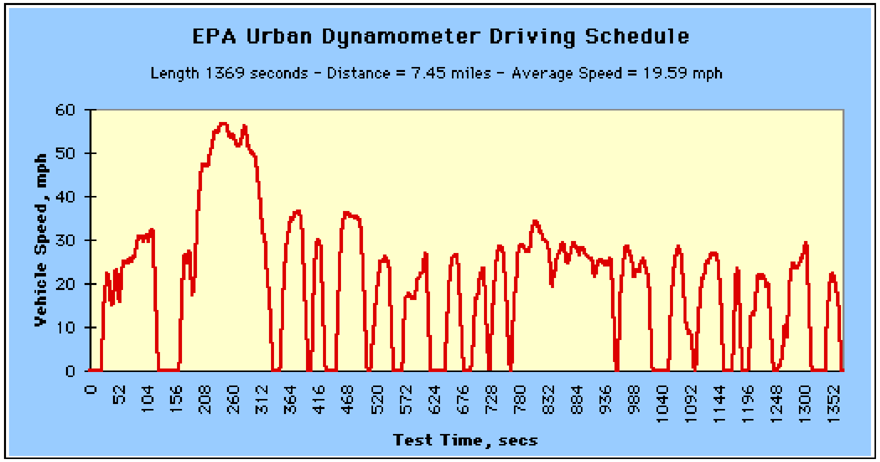
Transient heating conditions are very common in microelectronics, radio-frequency power amplifiers, vehicles and airliners.

<u>Transient heating in the advanced driver-assistance systems</u>



Shinoda, Electronics Cooling 2019

<u>EPA Urban Dynamometer Driving Schedule</u>

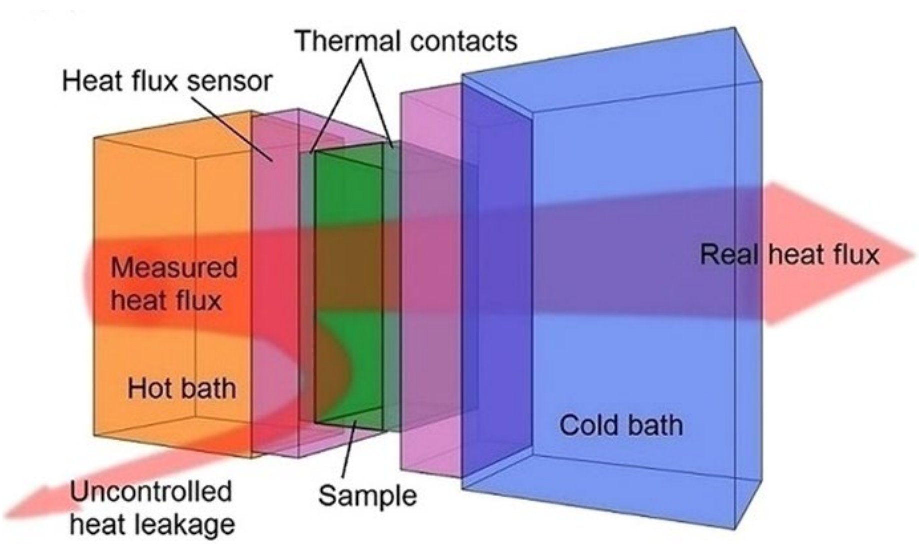


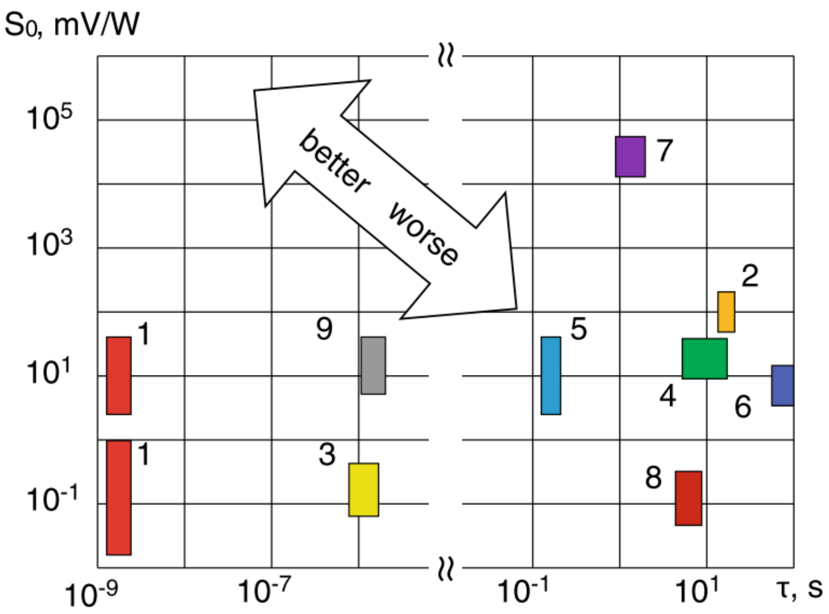
EPA

Heat Flux Measurements in Power Systems

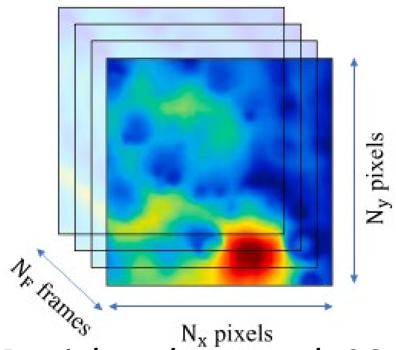
Surface-mounted sensors

- Transverse thermoelectric effect method
- Temperature gradient method
- Joule heating effect method

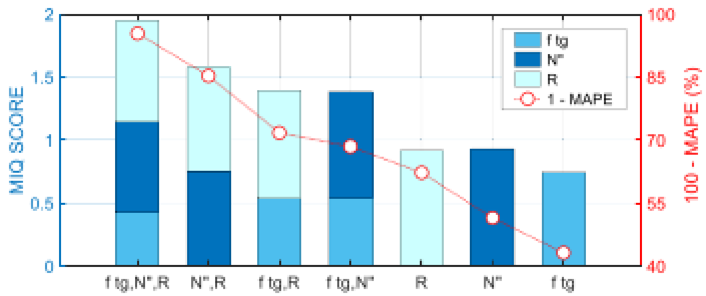




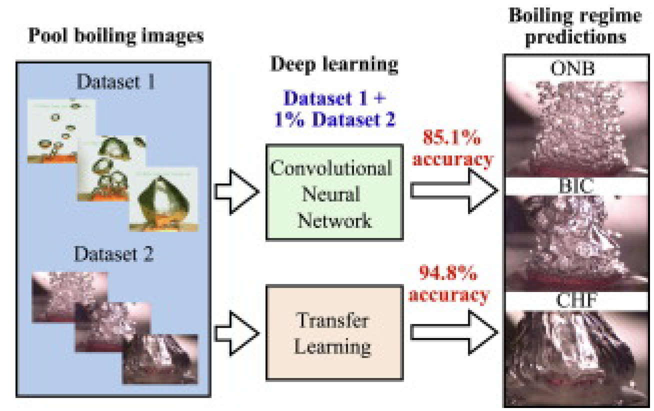
Deep Learning Strategies for Visualization-Based Analysis of Two-Phase Heat Transfer



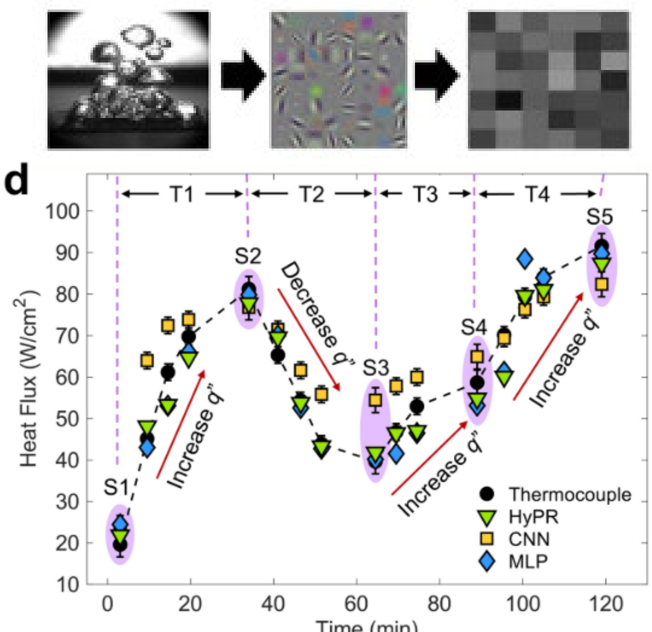
Ravichandran et al. 2019



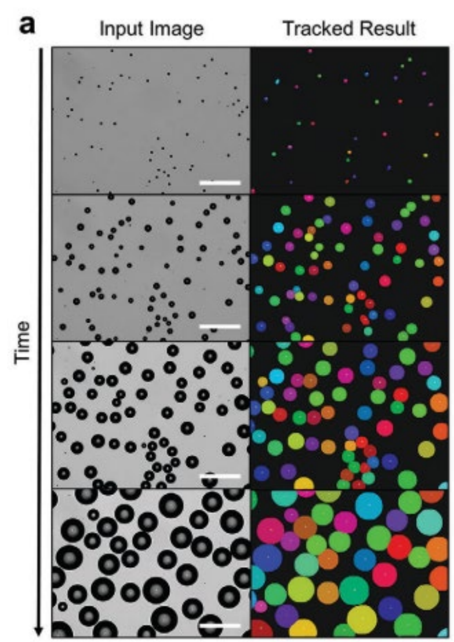
Ravichandran et al. 2021



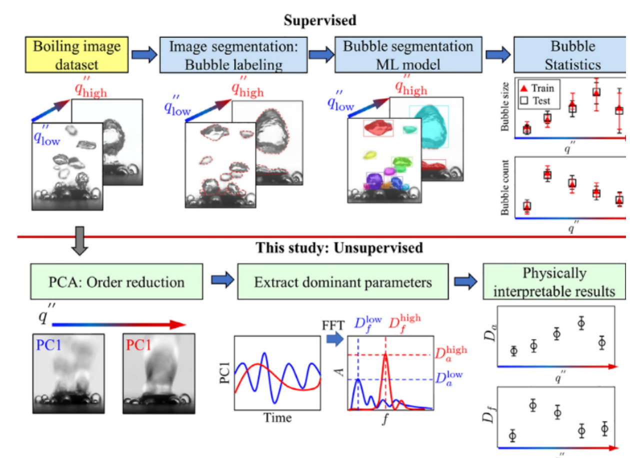
Rassoulinejad-Mousavi et al., ATE, 2021



Suh et al., Sci Rep, 2021



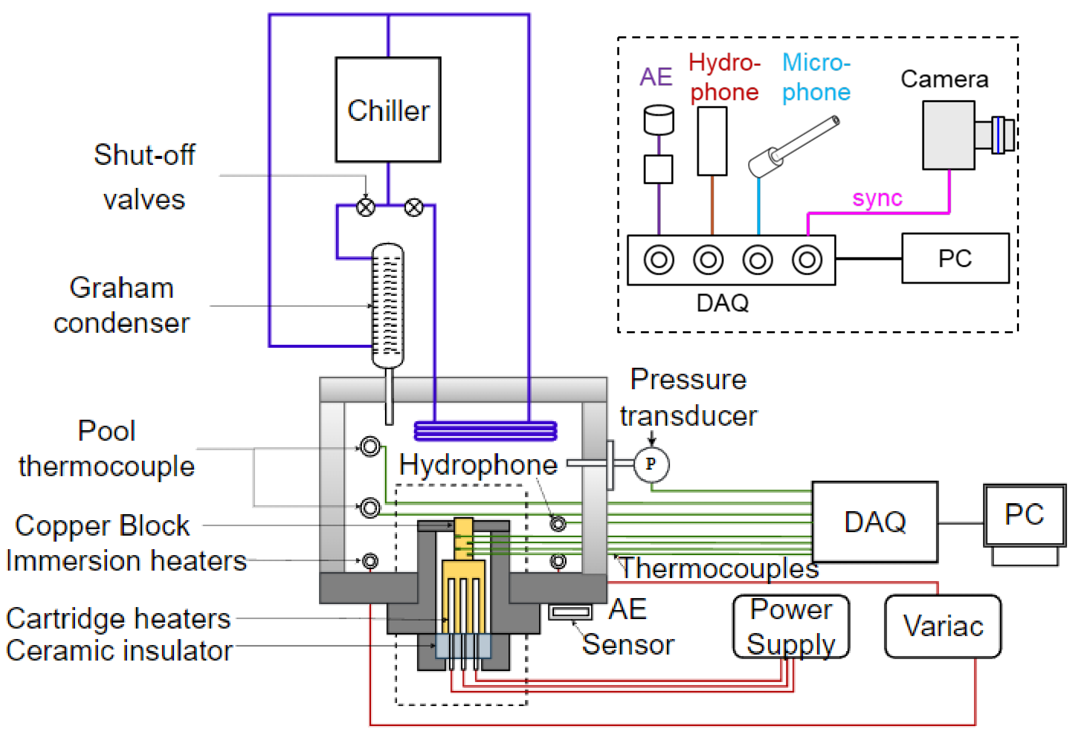
Suh et al., Adv Sci, 2021

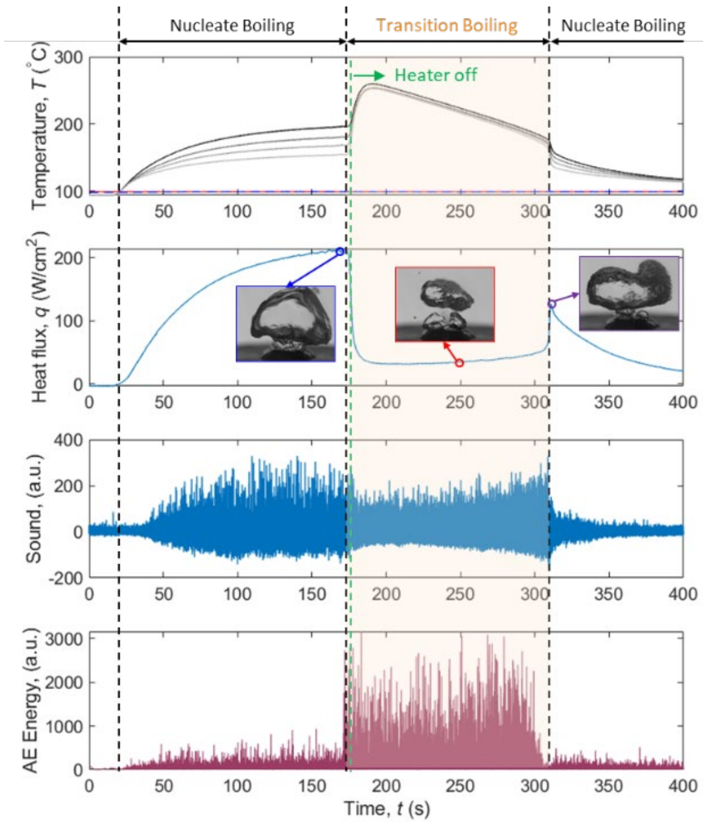


Rokoni et al., IJHMT, 2022

Pool Boiling Facility with Multimodal Sensing

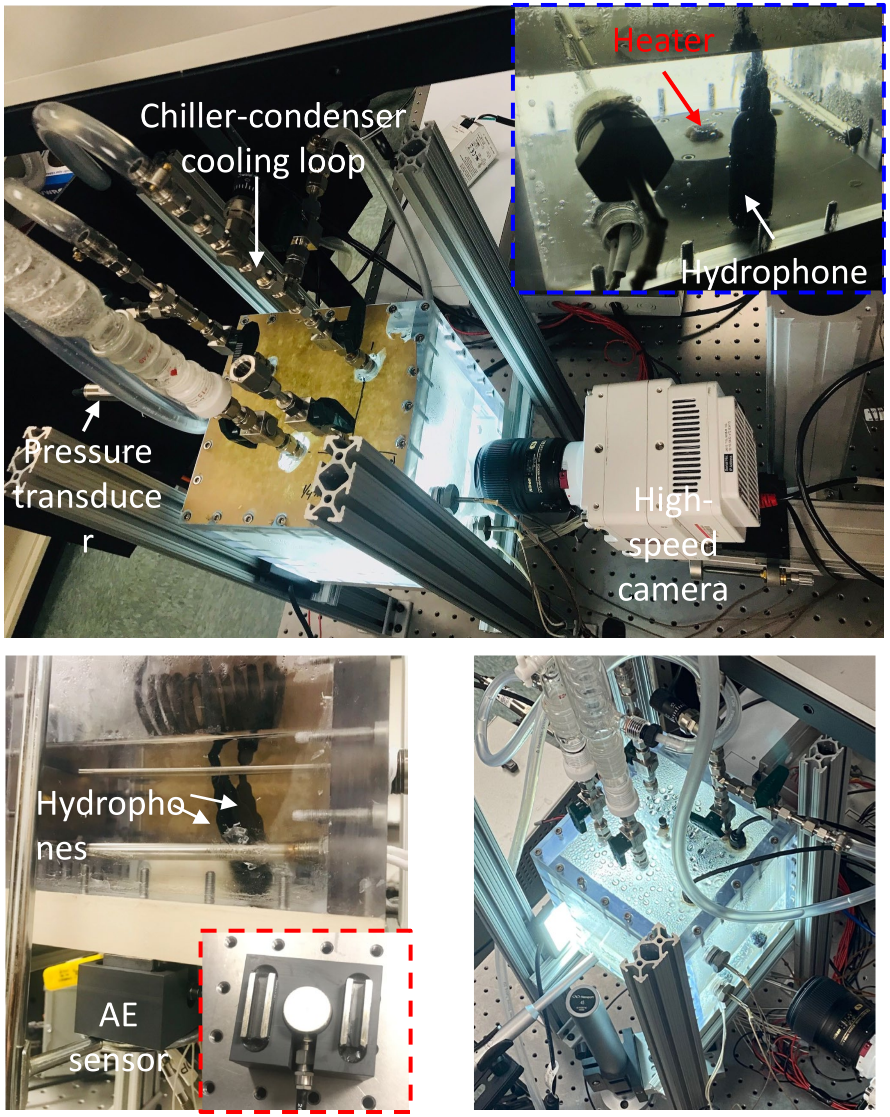
Synchronized multimodal Sensing: i) High-speed imaging, ii) acoustic – hydrophone, iii) acoustic – microphone, iv) acoustic – AE sensor, v) temperature profiles, vi) pressure.



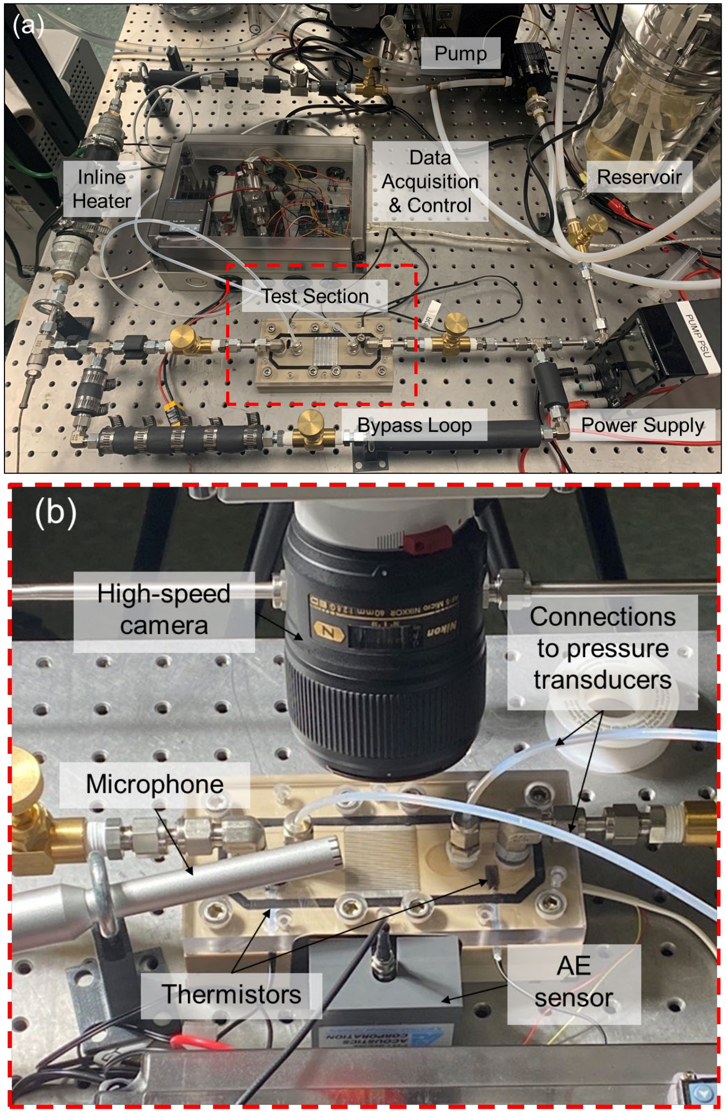


Multimodal Sensing in Boiling Systems

Pool Boiling

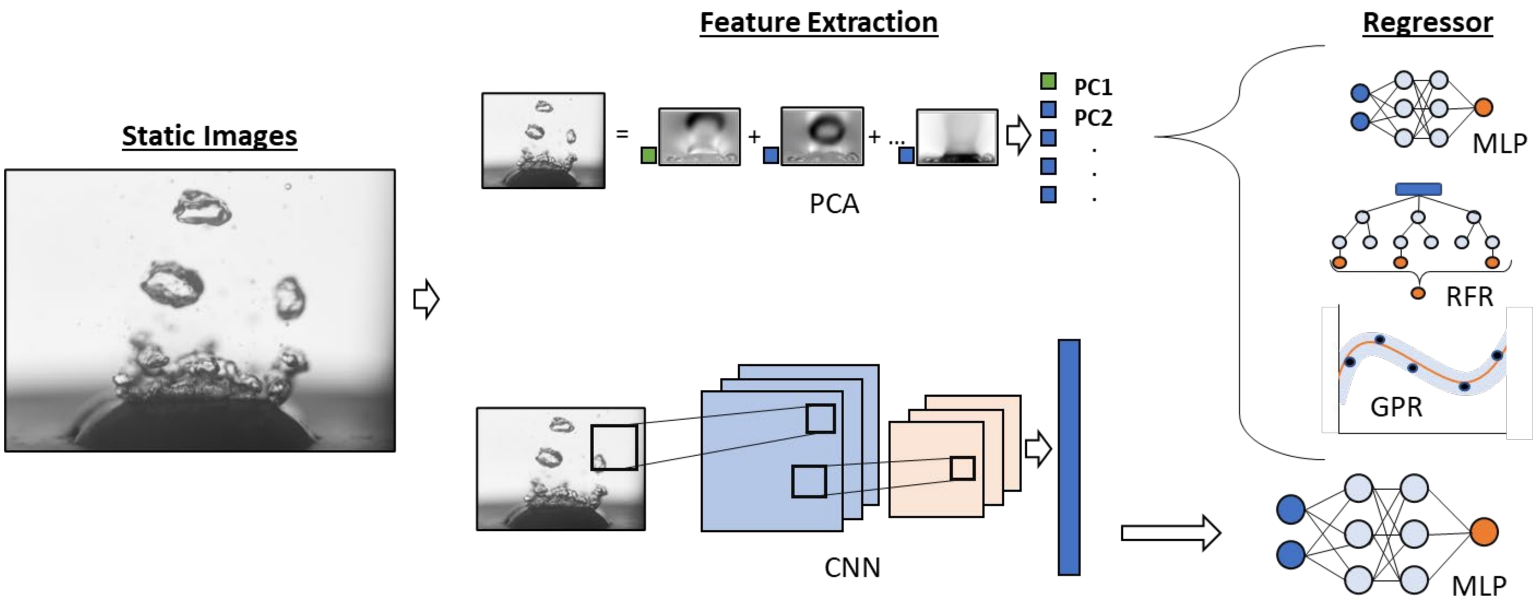


Flow Boiling

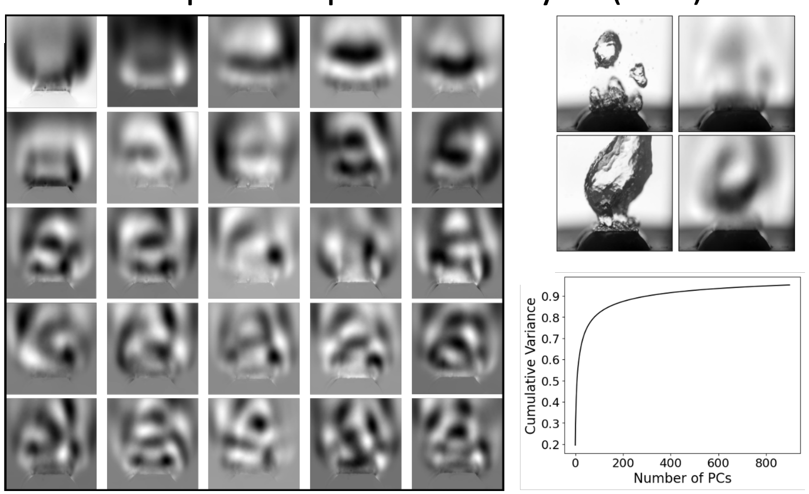


1. Visualization-Based Heat Flux Measurement

Existing Methods: Static Image-Based Heat Flux Prediction



Principal Component Analysis (PCA)



K-means Clustering

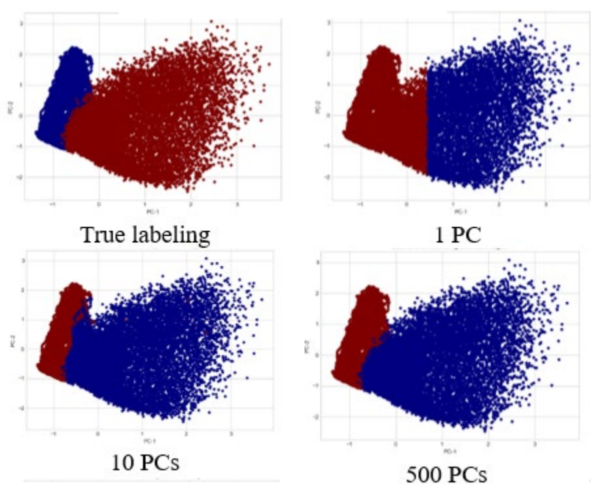
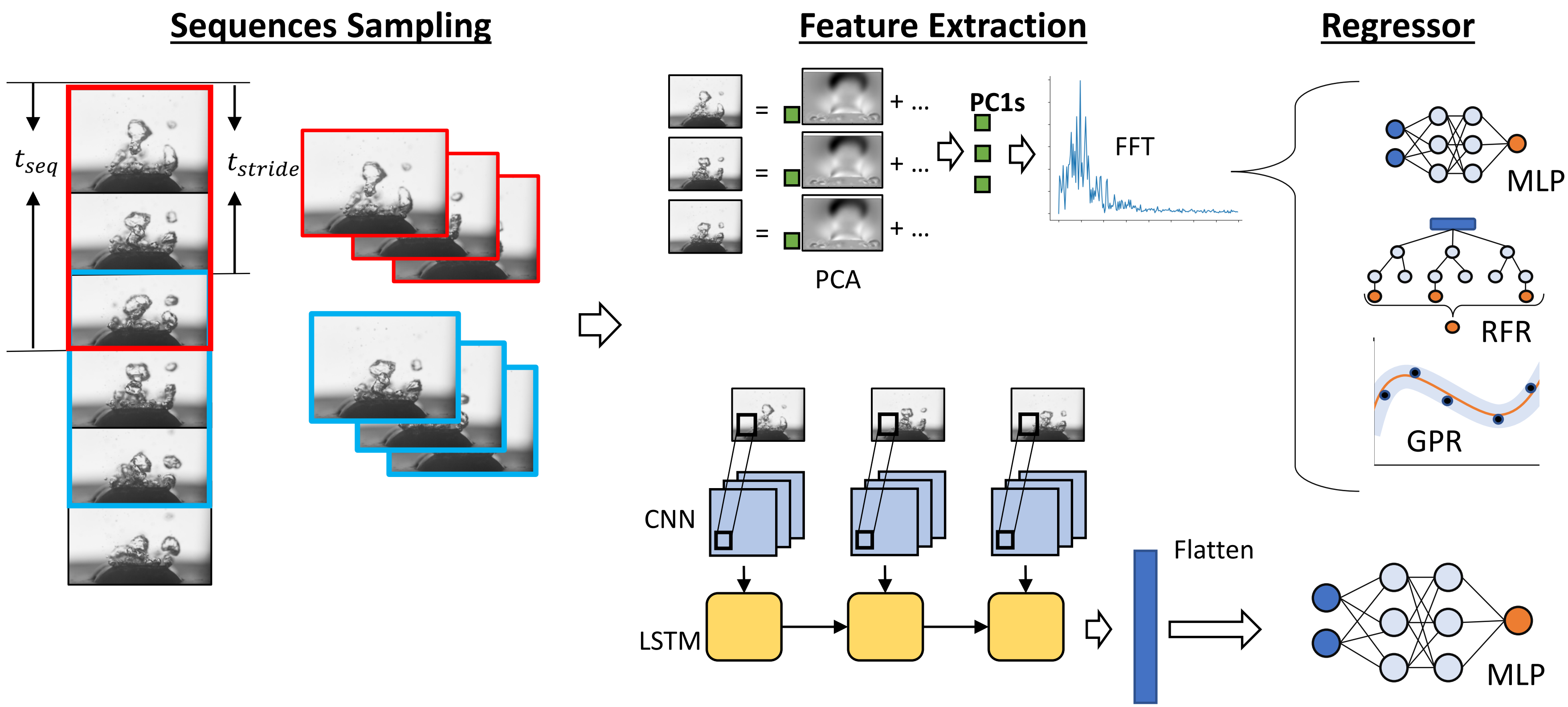


Image Sequence-Based Heat Flux Prediction



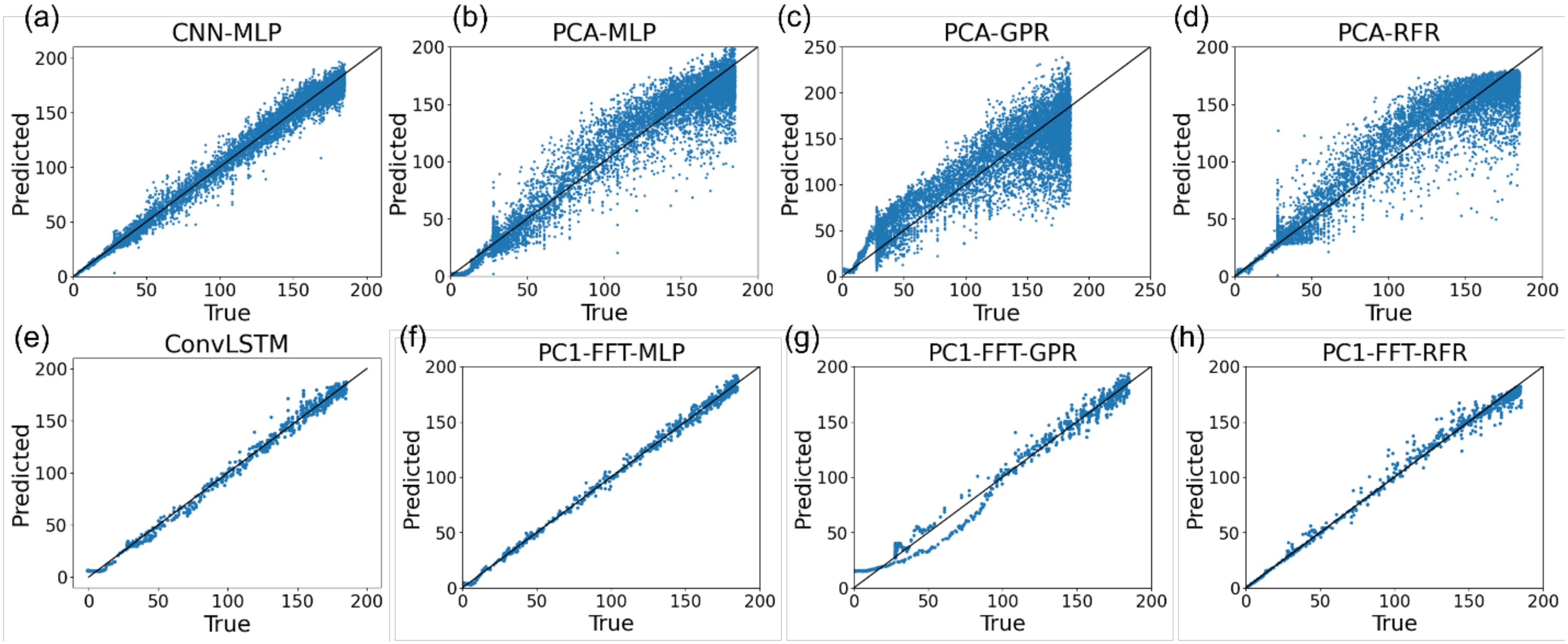
Spatiotemporal Feature Extraction:

- PCA and Fast Fourier Transform (FFT)
- Convolutional Long Short-Term Memory (ConvLSTM)

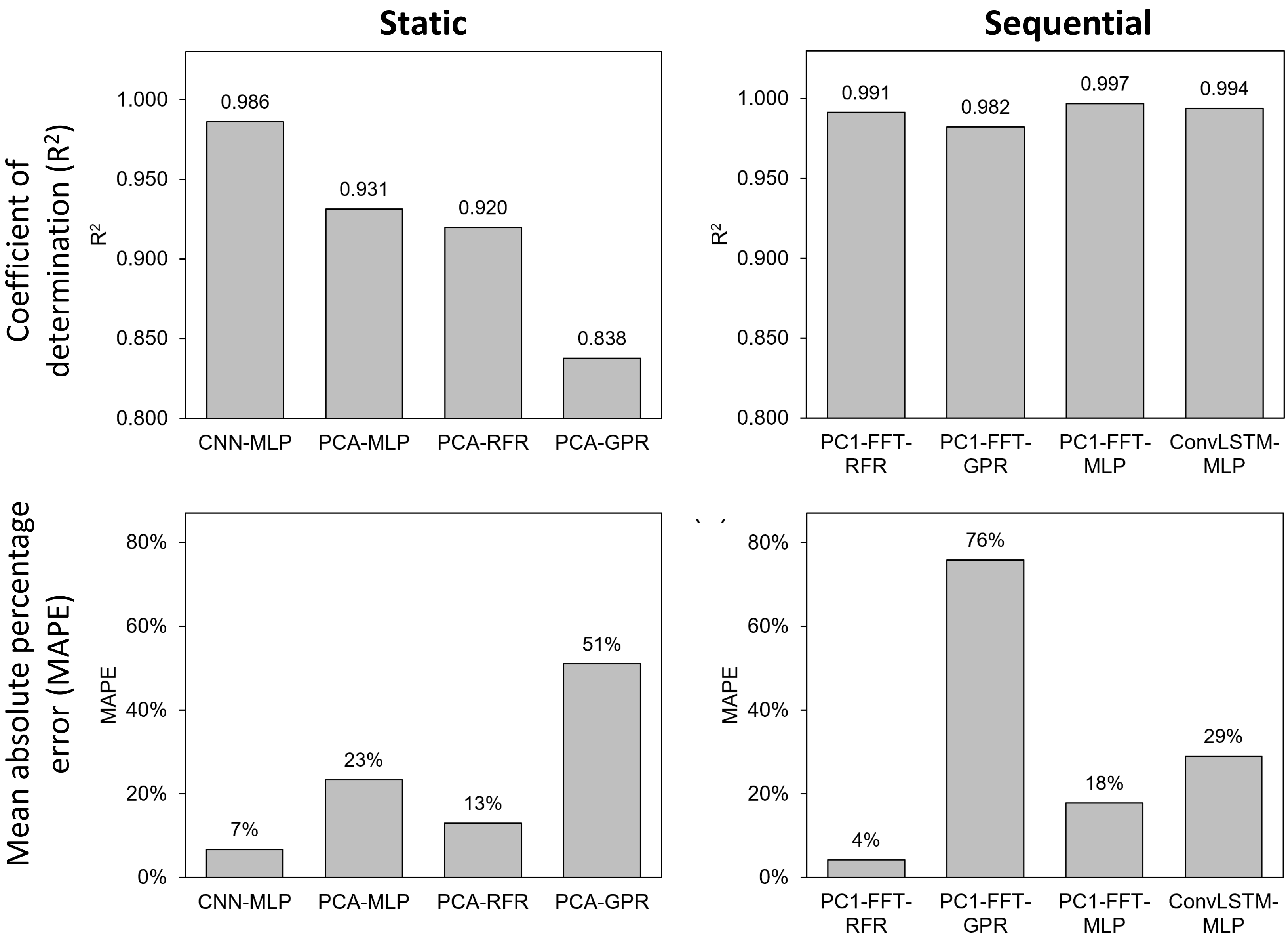
Heat Flux Prediction Performance: Static vs. Sequential

Model-predicted heat flux vs. true (experimental) heat flux for

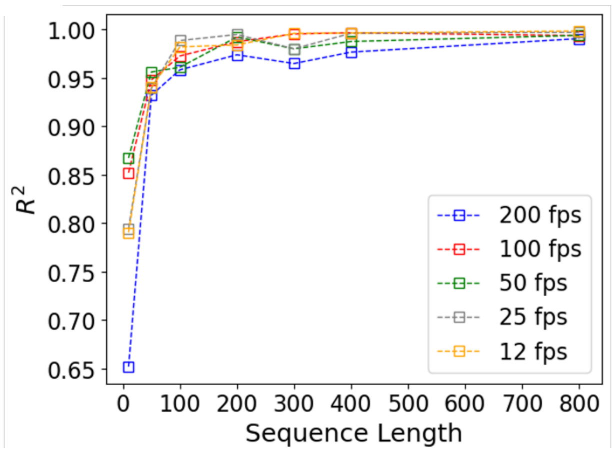
- static image models: CNN-MLP, PCA-MLP, PCA-GPR, PCA-RFR, and
- Image sequence models: ConvLSTM, PC1-FFT-MLP, PC1-FFT-GPR, PC1-FFT-RFR

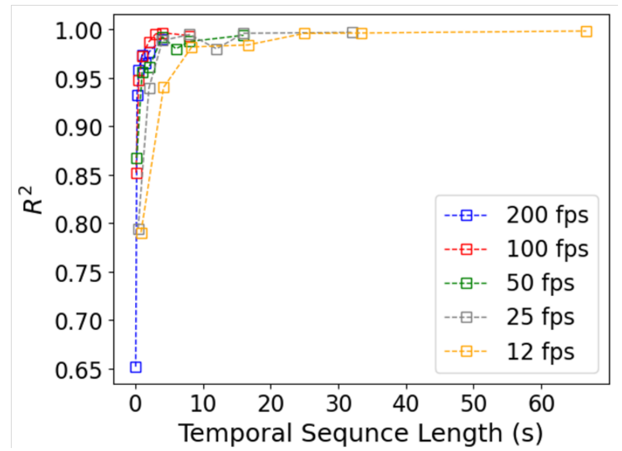


Heat Flux Prediction Performance: Static vs. Sequential

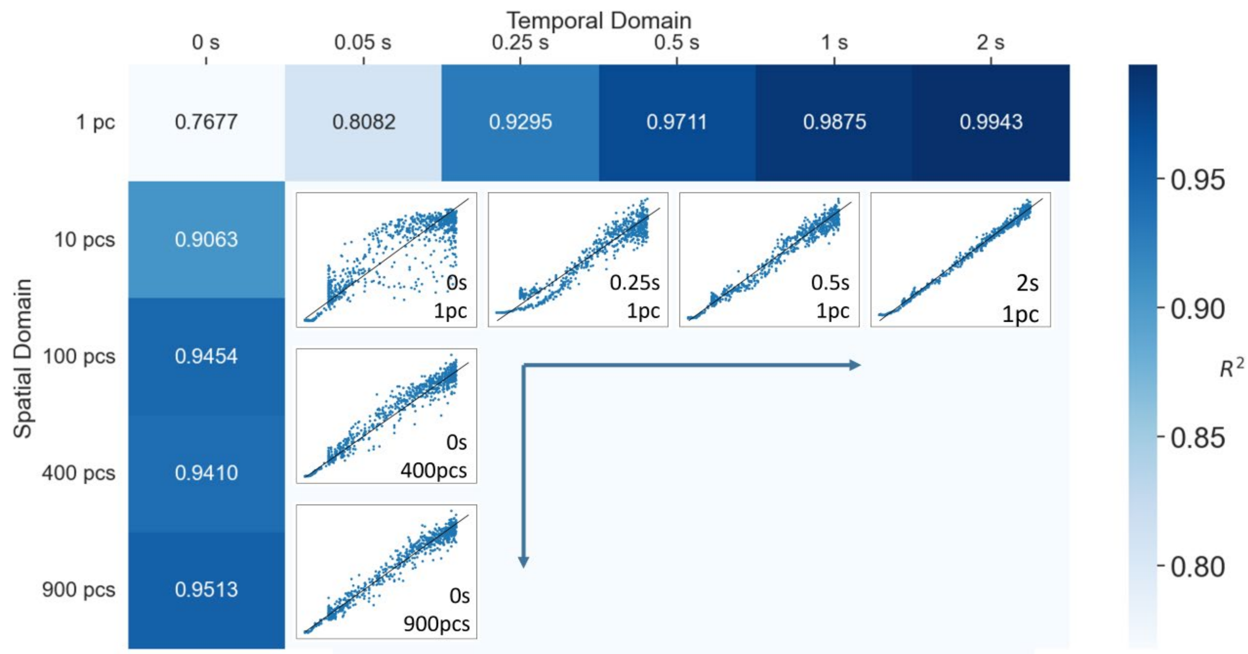


Role of Temporal Features of Bubble Dynamics on Heat Flux Predictions



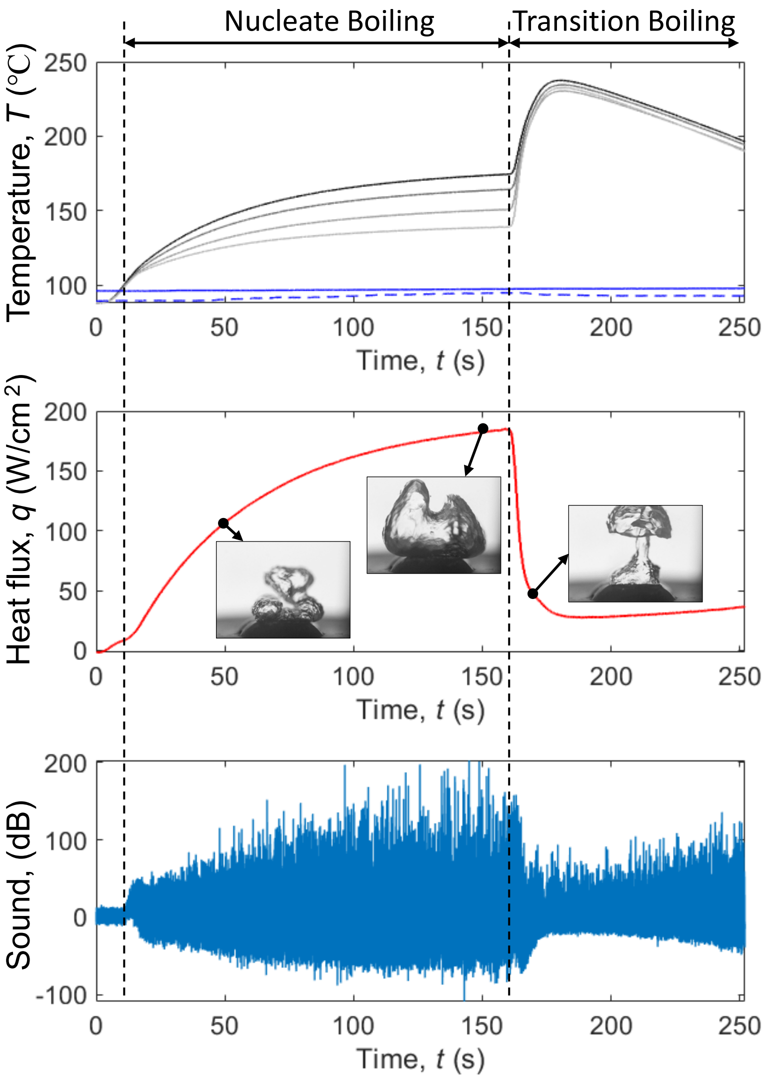


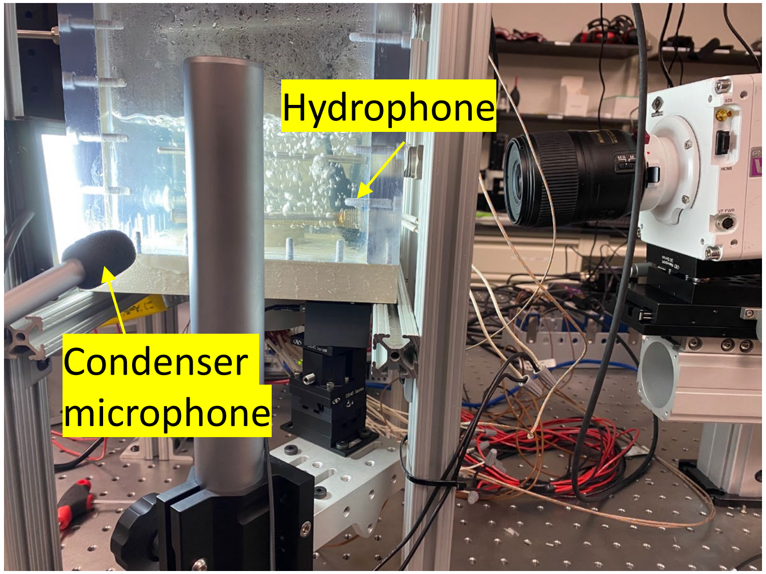
- Temporal features play a critical role in heat flux predictions.
- Larger temporal length leads to better prediction performance.
- The frame rate doesn't play a critical role when it's beyond 25 fps.

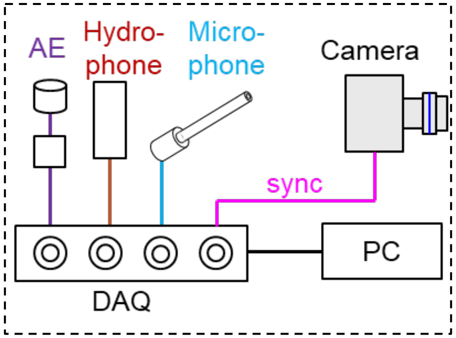


2. Acoustic-Based Heat Flux Measurement

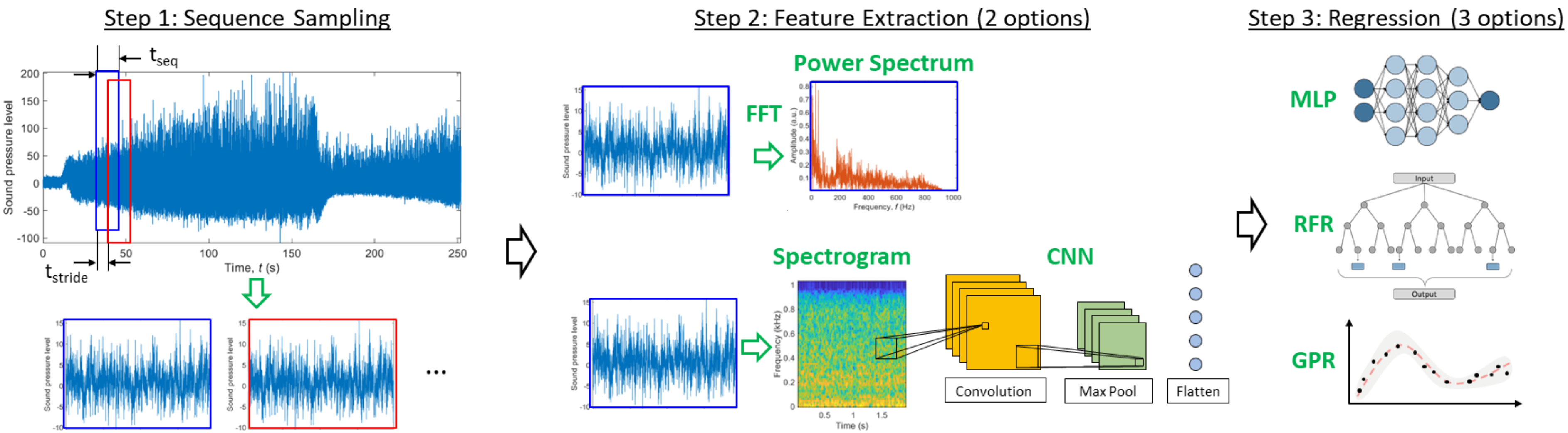
Acoustic Sensing in Pool Boiling Experiments



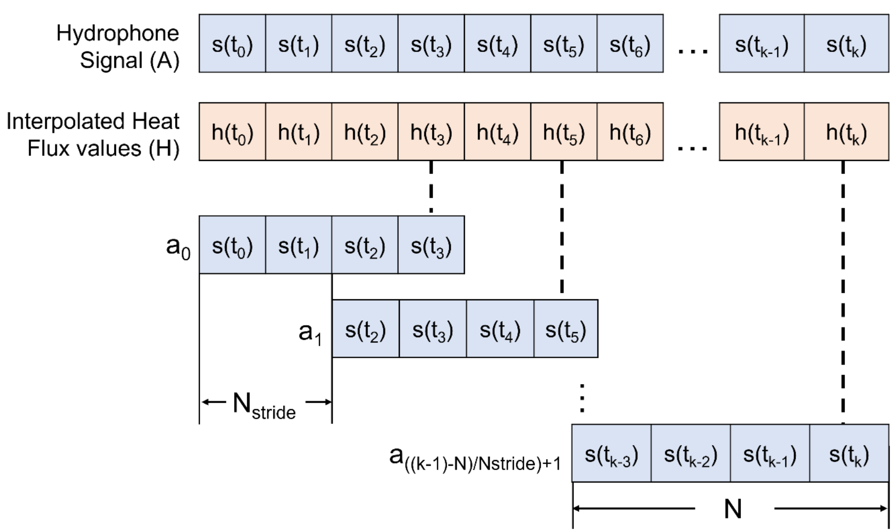




Machine Learning Algorithm for Heat Flux Prediction

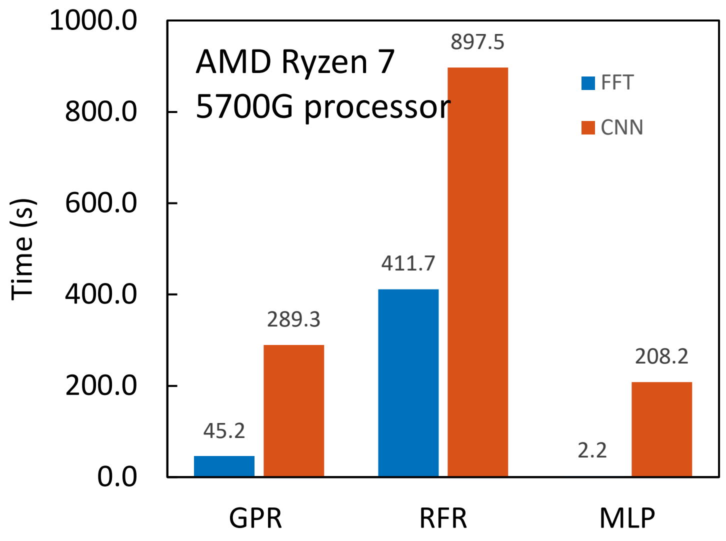


Sequence Sampling

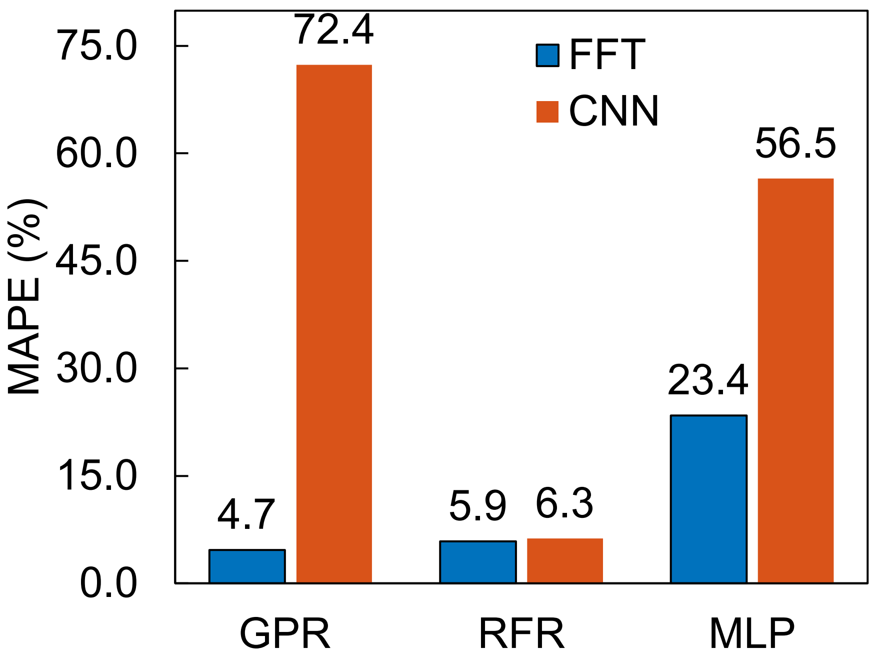


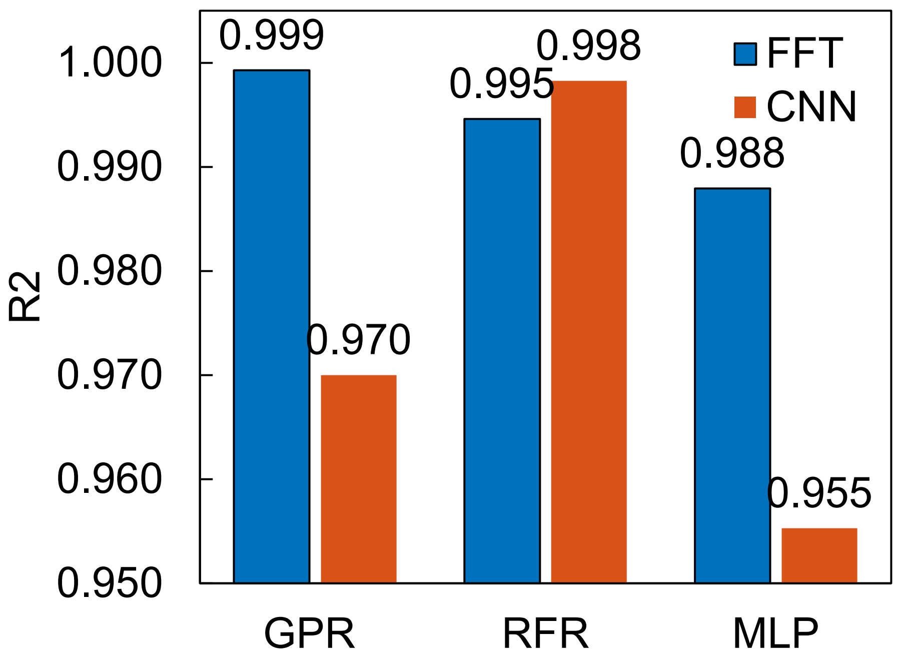
- Sequence length: number of frames
- Stride: frames to skip
- Frame rate: sampling rate
- Temporal sequence length: sequence length / frame rate

Model Performance and Computational Time for Training



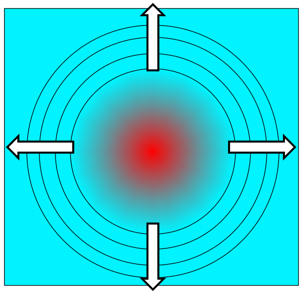
FFT-GPR model leads to high performance and low computational time.



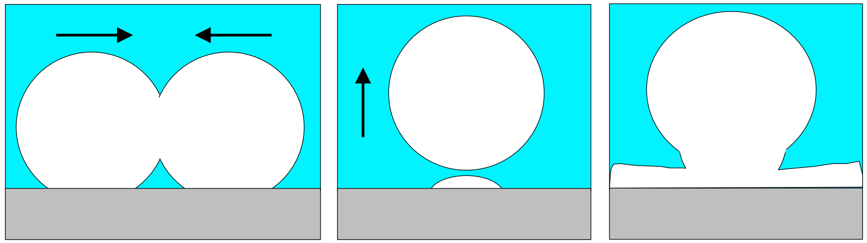


Physical Mechanisms of Acoustic Signals

Thermal Expansion



Bubble Ebullition

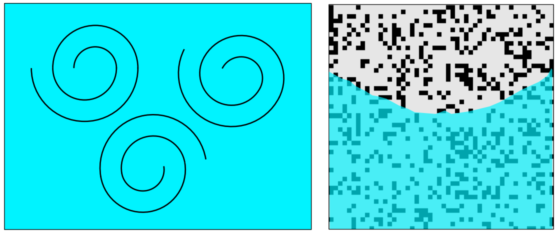


Bubble Coalescence

Bubble departure

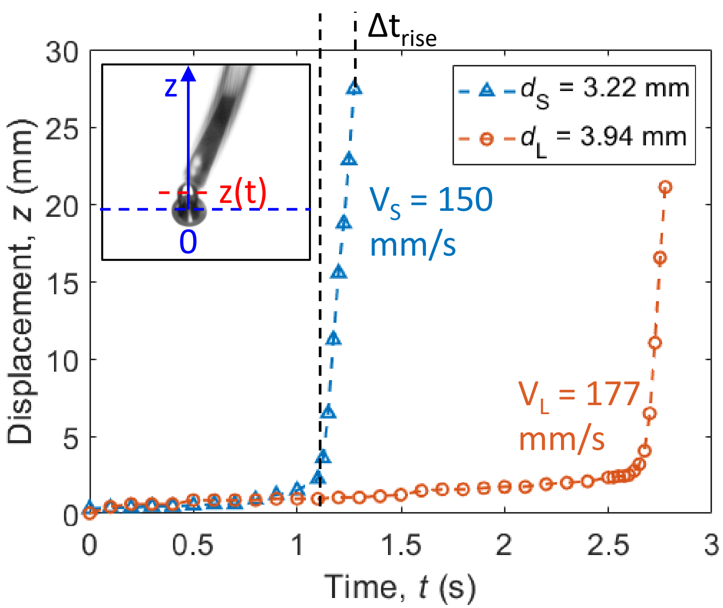
Critical Heat Flux

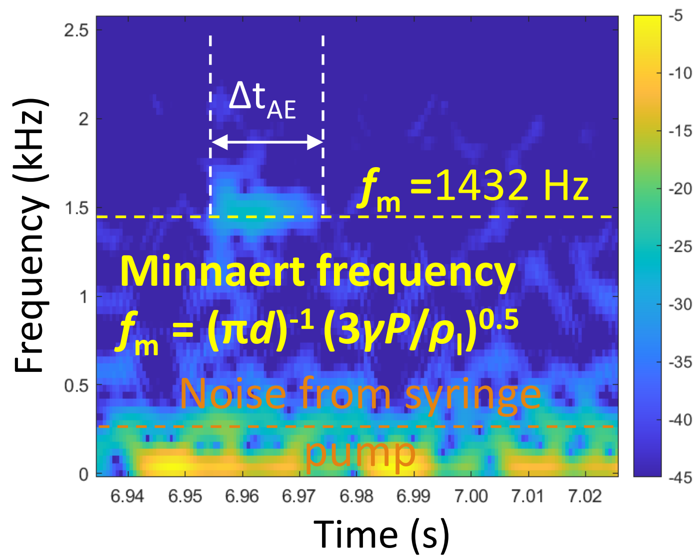
Flow-Structure Interaction



Convection

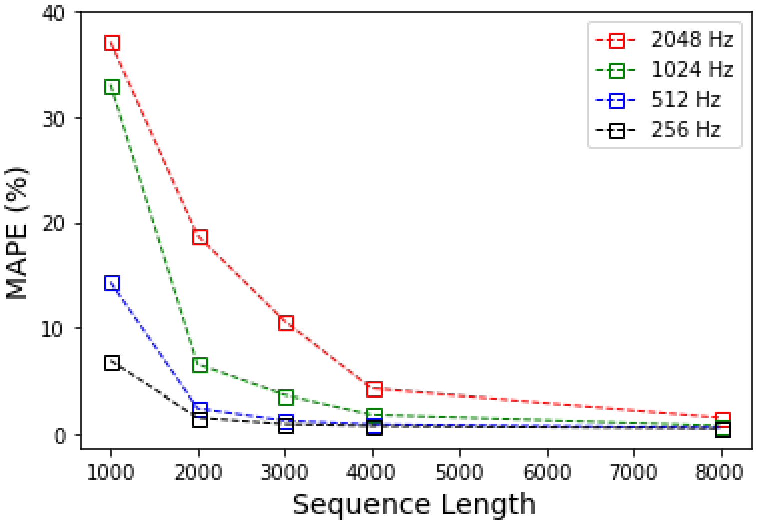
Capillary wicking

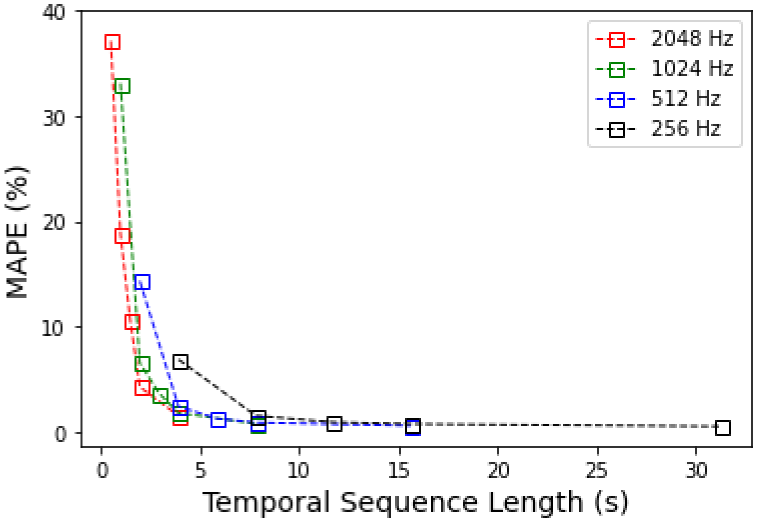


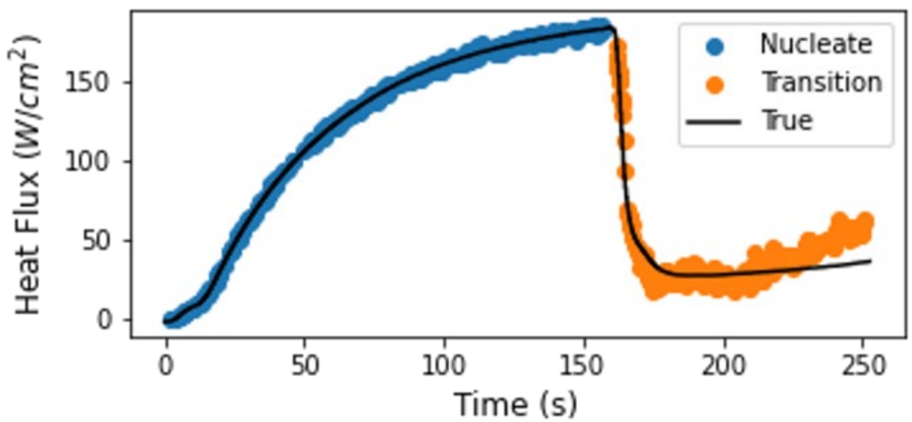


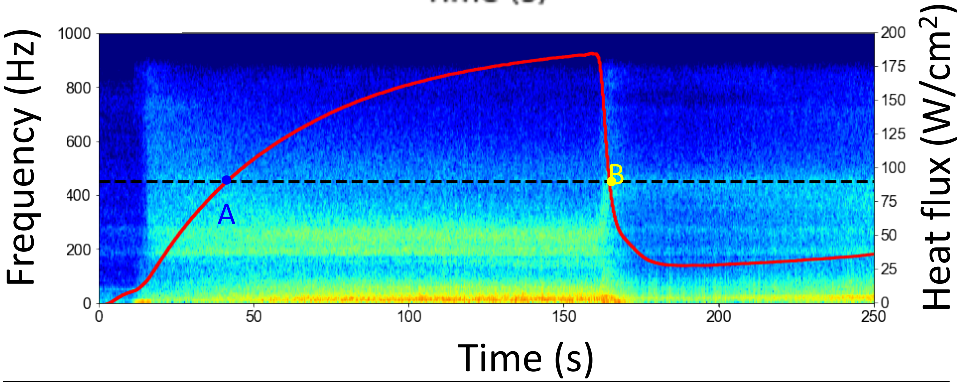
Bubble release: Verification against theory

Effect of Temporal Length and Boiling Regime





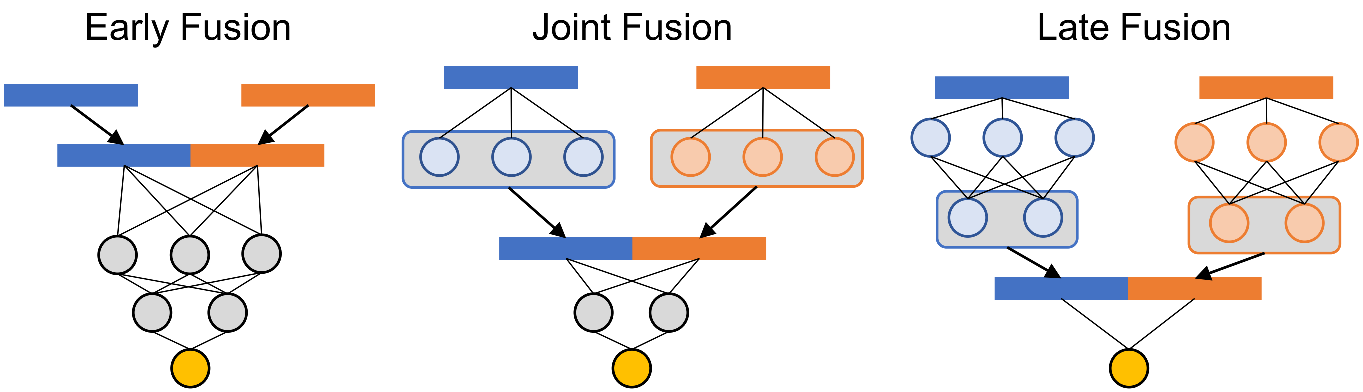




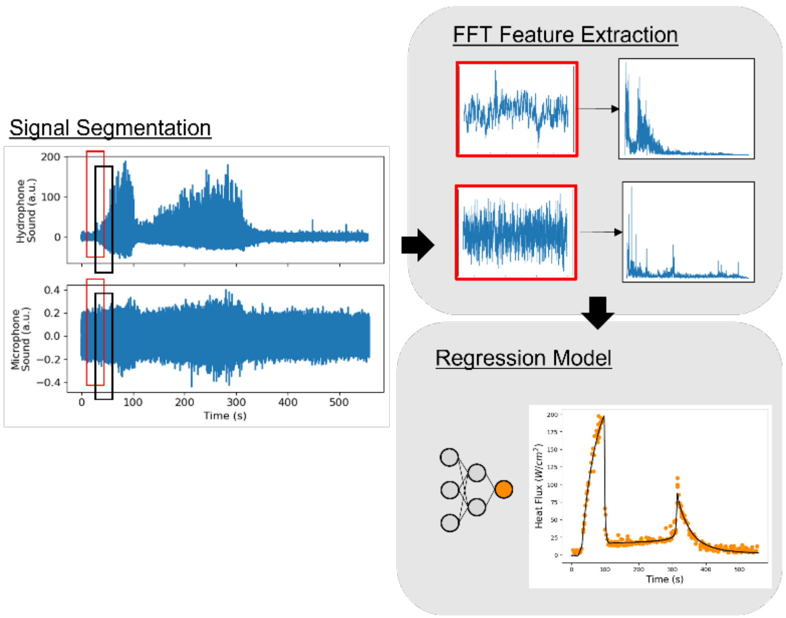
- Prediction accuracy is determined by temporal length rather than sequence length (number of frames)
- The boiling regime affects boiling heat flux prediction accuracy.

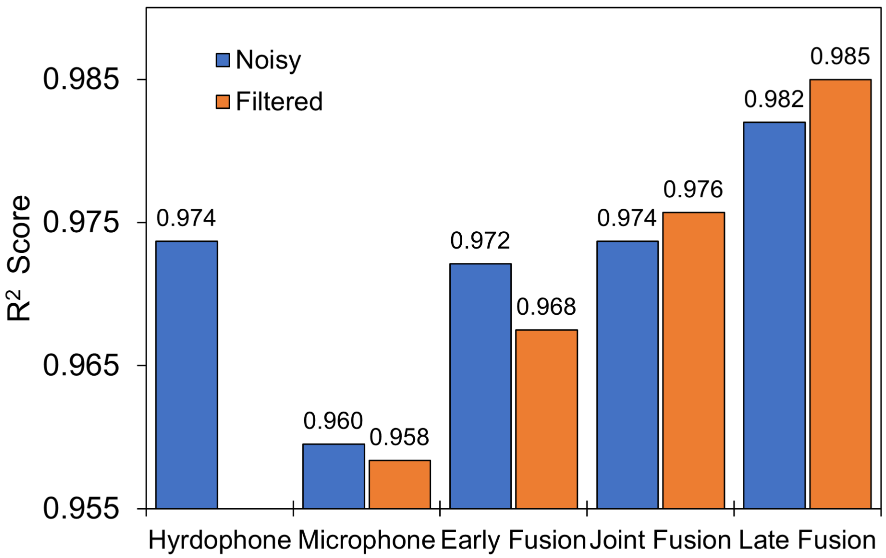
3. Multimodal Fusion for Heat Flux Measurement

Multimodal Acoustic Sensing and Data Fusion

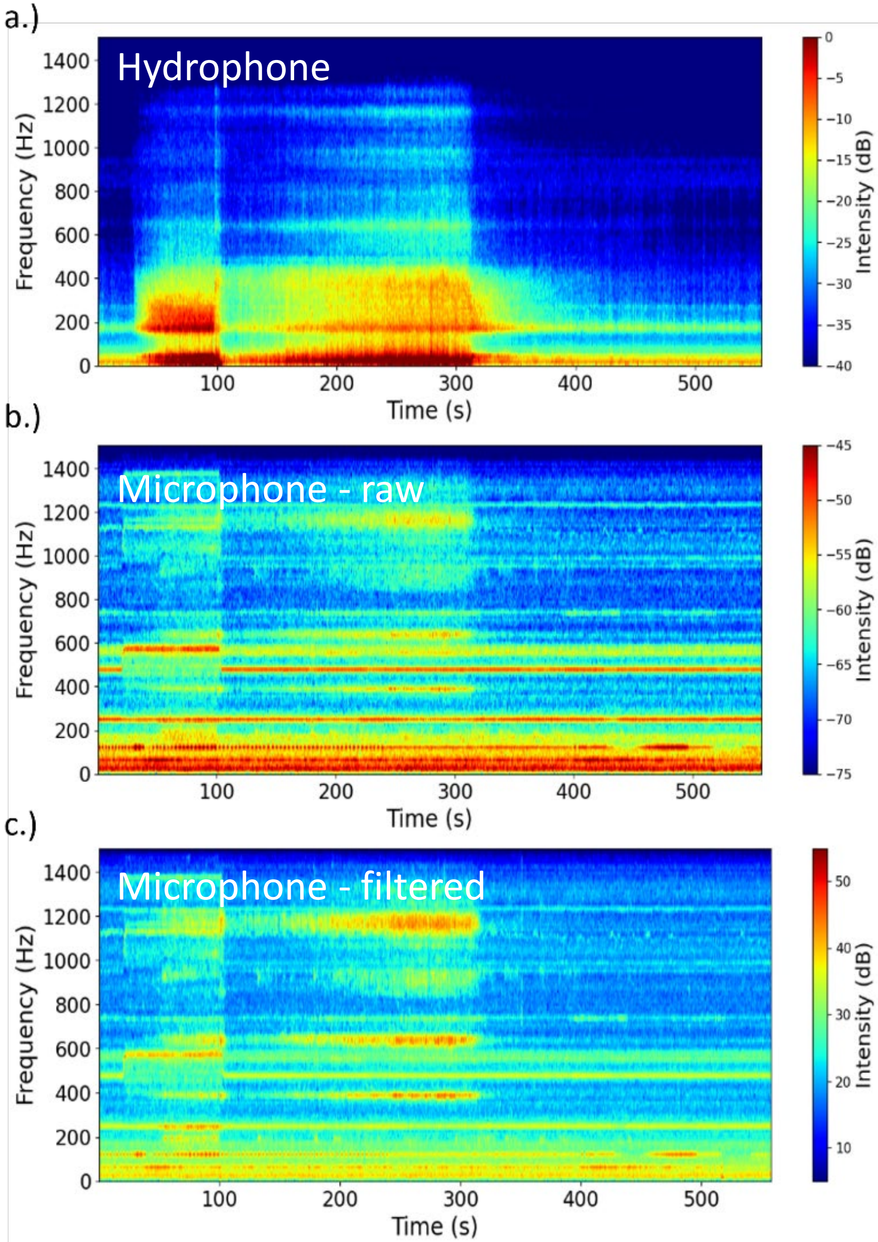


- Microphone: remote, noisy
- Hydrophone: immersion, clean

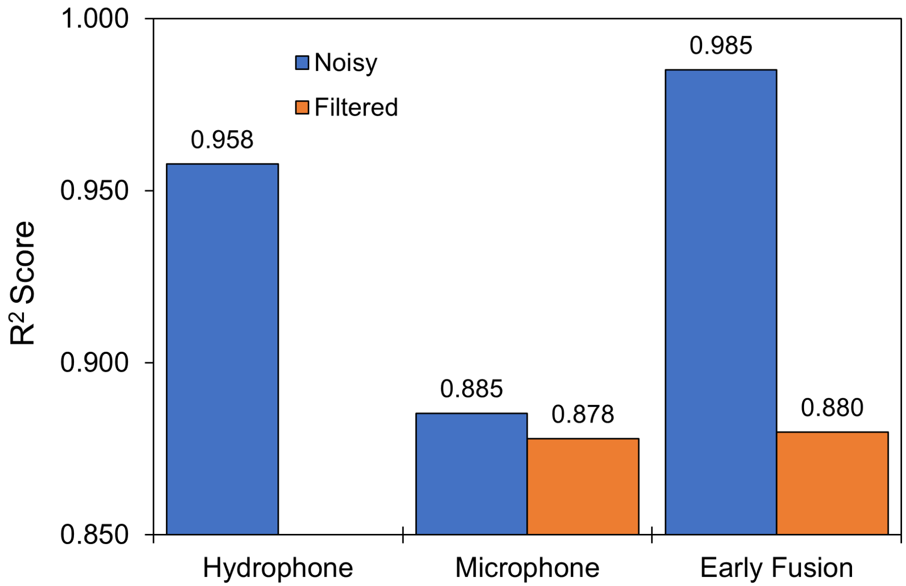




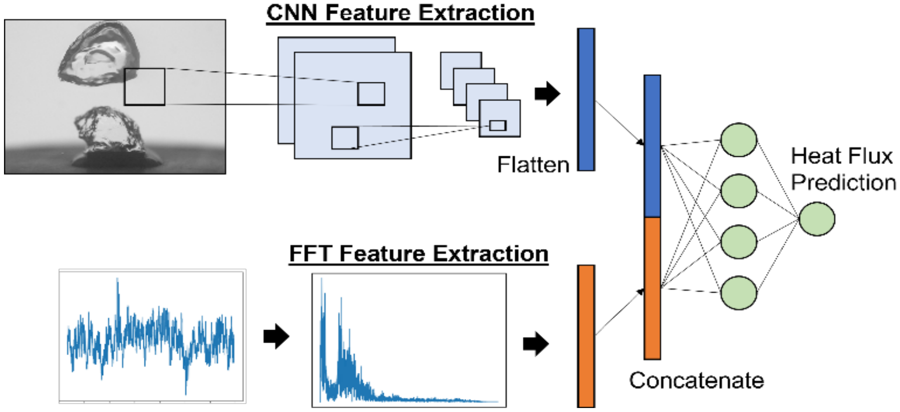
Effect of Denoising and Fusion on Heat Flux Measurements



Spectrogram of hydrophone, microphone (raw), and microphone (filtered).

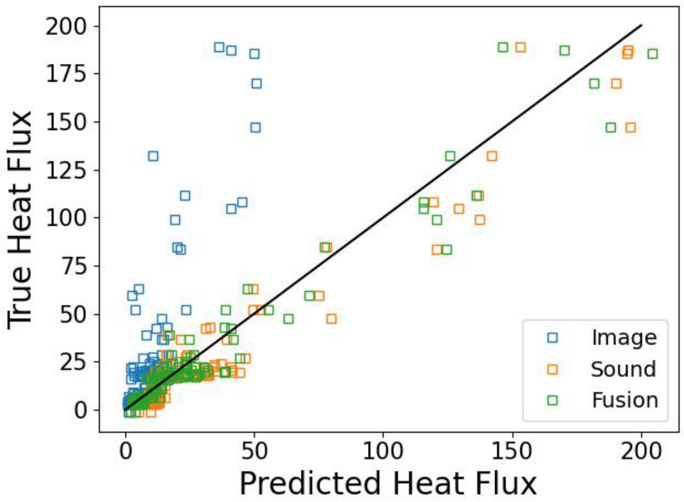


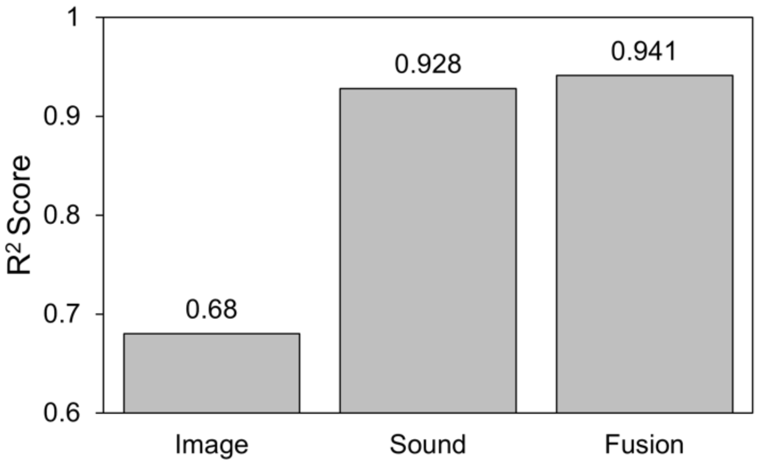
Audio-Video Fusion for Improved Prediction Accuracy



Audio-video fusion

- Static Image – CNN
- Acoustic sequence – FFT
- Fusion: concatenation





Acknowledgment

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The experimental side of the work is supported by Arkansas NASA EPSCoR RID through ASGC and University of Arkansas Chancellors' Funds for Innovation and Collaboration, Commercialization, and GAP.

NSF and NASA I-Corps

NSF Regional I-Corps, Texas State I-Corps Site for Entrepreneurship

- Entrepreneurial Lead (EL): Hari Pandey (ART)
- Date: 10/14/2021 – 11/4/2021
- Interviews completed: 27

NSF National I-Corps, VentureWell

- EL: Hari Pandey (ART)
- Date: 3/14/2022 – 4/26/2022
- Interviews completed: 102

NASA I-Corps Short Course, NSF I-Corps Hub Southwest

- EL: Najee Stubbs & Christy Dunlap (AcoustiFlux)
- Date: 4/28/2023 – 5/26/2023

Ms. Catherine Corley served as the I-Corps Mentor for both teams

Selected Interviewee Affiliations

- TESLA
- Aurora
- Azure
- CoolIT systems
- Georgia Institute of Technology
- NOKIA Bell Labs
- intel
- TOYOTA RESEARCH INSTITUTE
- Munters
- UF UNIVERSITY of FLORIDA
- Kelvin Thermal
- GE Research
- CYBER SCIENCES
- Google Cloud Platform
- THE UNIVERSITY of TULSA
- INTUITIVE SOLUTIONS
- AMD
- Google
- GCTG Global Cooling Technology Group
- ACT
- OzIC
- Qualcomm
- UNIVERSITY OF WOLLONGONG IN DUBAI
- Mizzou University of Missouri
- Wolfspeed
- embro Specialist for Smart Textiles
- AMBOTS
- STREAM DATA CENTERS
- THE UNIVERSITY OF TOLEDO

What we did and what we found?

Advanced Cooling

Manufacturing/ industries

Vehicles

Integrated Circuits/ Electronics

"Thermal failures occurs due to discrepancies in flow rates, system oversize, and cooling capacity"
- Marc (Liquid immersion specialists)

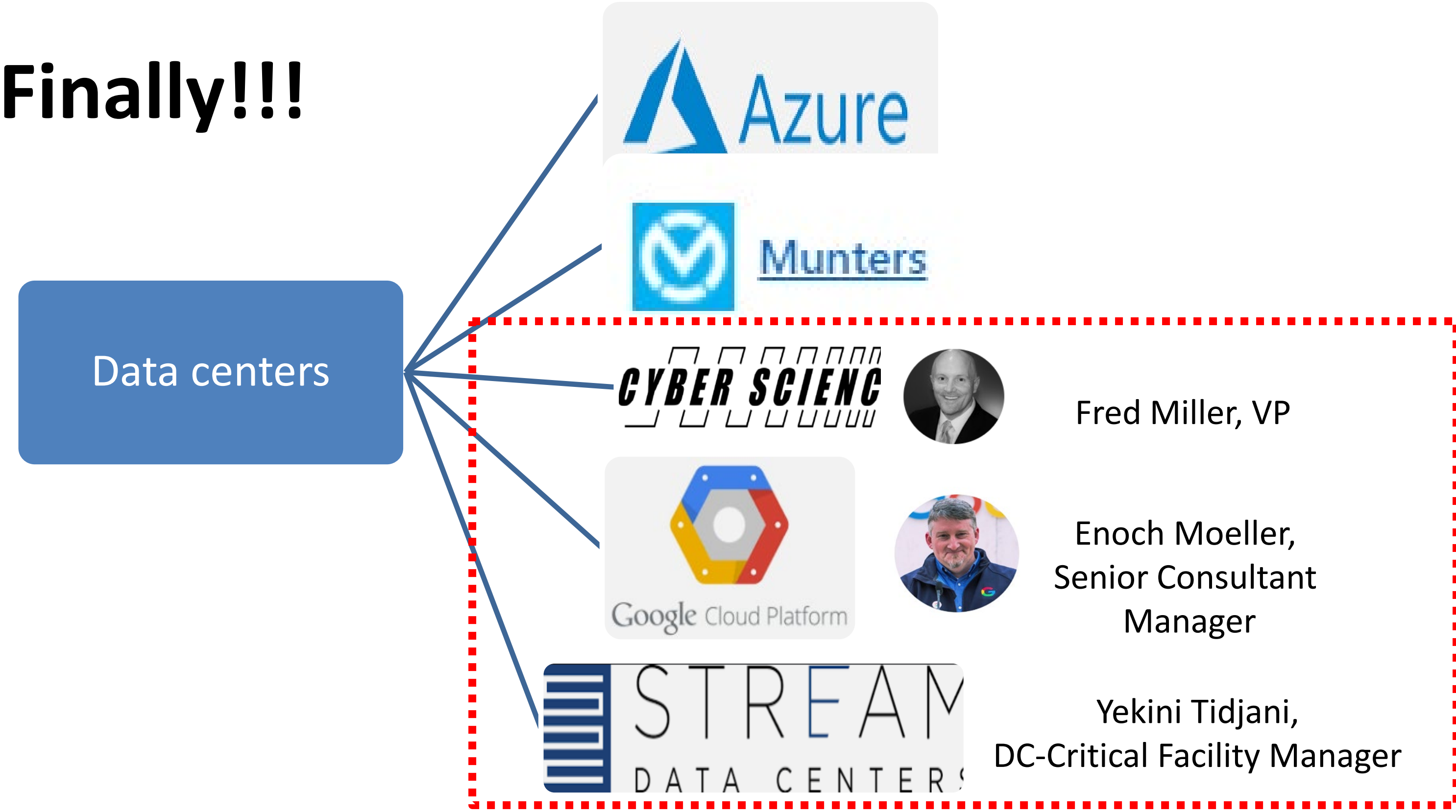
"Industry look at the practicality of solutions with structural integrity"
- Hamed (Senior thermal engineer)

"Non-intrusive methods could be important way for thermal monitoring in future"
- Shoaib (Senior research engineer)

"Non-intrusive methods would be great but need to make sure it checks temperature precisely"
- Balaji (Senior electronic design engineer)

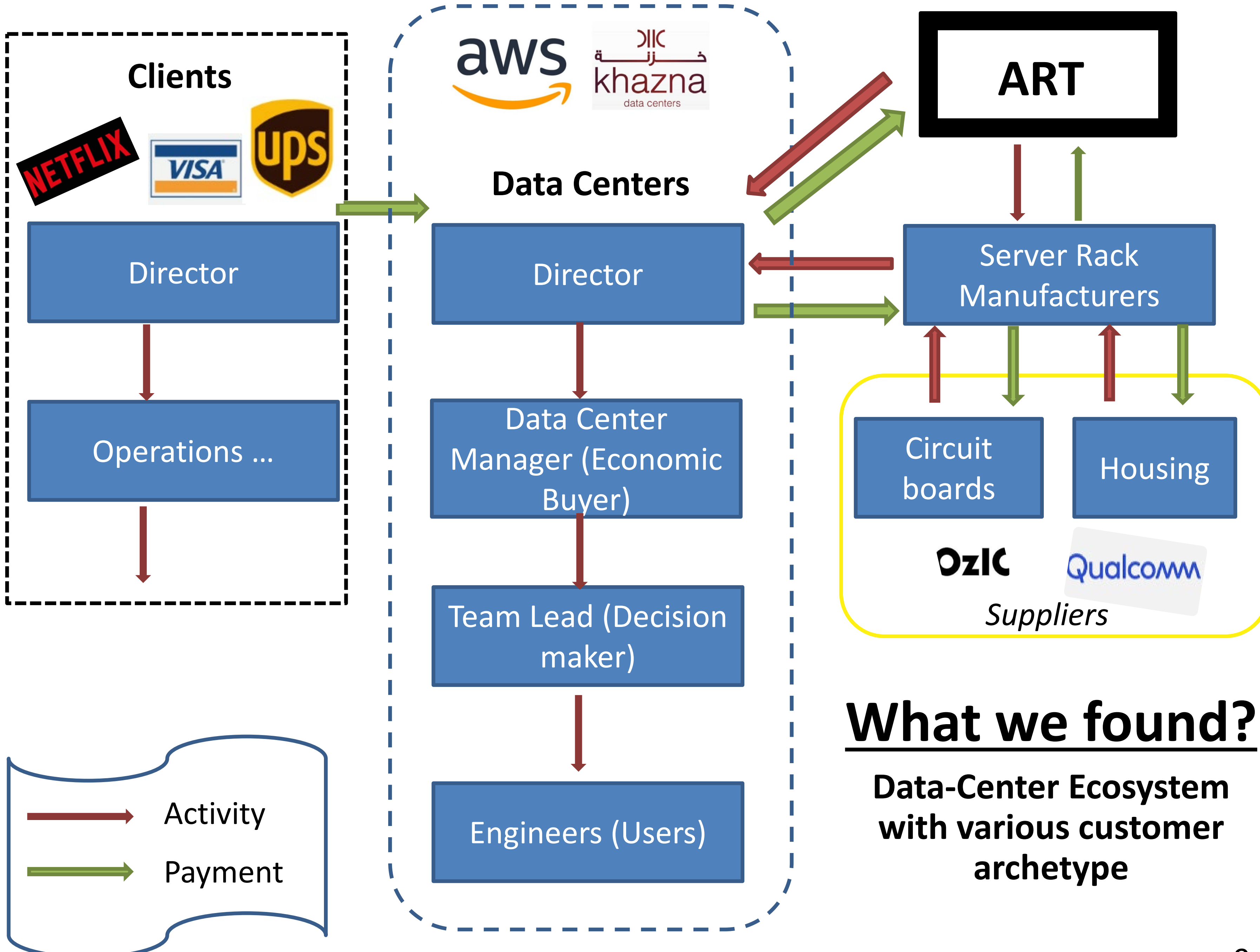
"Electronics working on extreme environments need better thermal control"
- John (CEO)

Finally!!!



Enoch: Google's data centers have their dedicated electrical power distribution system with transformers. High-voltage transformers are effective to reduce power loss and improve PUE

Fred: Data centers watch closely on power consumption rates and usage effectiveness. The prevalent of power related outages has increased industry's concern over real-time monitoring of power distribution and electrical systems.



What we found?

Data-Center Ecosystem with various customer archetype

Business Model Canvas

Key Partners

- Establish partnerships with key players in AE sensors field like MISTRAS

Key Activities

- Provide faster monitoring and feedback compared to typical available systems.
- Provide an easier way of replacing sensors than traditional sensors.

Key Resources

- Intellectual property
- MISTRAS Acoustic sensing and DAQ system
- Immersion cooling facility

Value Proposition

- Safe operation of data centers in extreme environments
- Reduce PUE by more than 30%.

Customer Relationships

- Get: Speak at technical conferences, publish white papers
- Keep: Provide webinars focusing on customer's events
- and monthly status update on technology
- Grow: Co-creation

Channels

- Direct Channel
- OEM channel

Customer Segments

1. Senior Research Engineer (Decision-Maker)
2. Data center Manager (Economic Buyer)
3. Thermal Engineers (User)

Cost Structure

- Materials and R &D cost for the development of prototype
- After successful testing, costs comprise of labor, marketing, and materials of the product.

Revenue Streams

- Asset sale: Acquisition by datacenters

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Publications Acknowledging DART Seed Grant

Journal articles (2):

- C. Dunlap, H. Pandey, E. Weems, and H. Hu, “Nonintrusive Heat Flux Quantification Using Acoustic Emissions During Pool Boiling,” 120558, 2023.
- C. Dunlap, S. Featherstone, M. Smith, M. Vu, A. Williams, J. Bailey, and H. Hu, “Design and Fabrication of A Low-Cost and Programmable Dip Coating Machine,” HardwareX, 12, e00364, 2022.

Conference proceedings (8):

- Y. Xu, B. Zhao, S. Tung, and H. Hu, “Infusing Data Science into Mechanical Engineering Curriculum with Course-Specific Machine Learning Modules,” in 2023 ASEE Annual Conference, Jun 2023, Baltimore, MD, 38680.
- S. Pierson, N. Nawar, and H. Hu, “Comparing the Heat Removal Efficiency of Microchannel Heat Sinks Produced by CNC Milling Versus Powder Bed Fusion” in ASTFE 8th Thermal and Fluids Engineering Conference, TFEC-2023-45992.
- H. Hu and C. Heo, “Integration of Data Science into Thermal-Fluids Engineering Education”, in Proceedings of the ASME 2022 International Mechanical Engineering Congress and Exposition, Oct – Nov 2022, Columbus, OH, IMECE2022-88193.
- C. Dunlap, H. Pandey, and H. Hu, “Supervised and Unsupervised Learning Models for Detection of Critical Heat Flux During Pool Boiling,” in Proceedings of the ASME 2022 heat Transfer Summer Conference, HT2022-85582.
- H. Pandey, W. Waldo, and H. Hu, “Non-Intrusive Cooling System Fault Detection and Diagnostics Using Acoustic Emission,” in Proceedings of the ASME 2022 heat Transfer Summer Conference, HT2022-85429.
- J. Marsh, C. Dunlap, S. Pierson, and H. Hu, “Introducing LabVIEW and Arduino as Data Acquisition System Alternatives,” in 2022 ASEE Midwest Section Conference, Sep 2022, Tulsa, OK, 3279.
- C. Dunlap, J. Pummill, and H. Hu, “Infusing High-Performance Computing and Machine Learning in Mechanical Engineering Education,” in 2022 ASEE Midwest Section Conference, Sep 2022, Tulsa, OK, 2944.
- S. Pierson, J. Goss, and H. Hu, “Enhancing Undergraduate Mechanical Engineering Education with CAM and CNC Machining,” in 2022 ASEE Midwest Section Conference, Sep 2022, Tulsa, OK, 6932.