

Supplementary Information for

Recent Progress of Artificial Intelligence for Liquid-Vapor Phase-Change Physics

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This PDF file includes:

Supplementary Table 1 | Literature summary of meta-analysis.

Supplementary Table 2 | Literature summary of physical feature extraction via ML.

Supplementary Table 3 | Literature summary of traditional computer vision methods.

Supplementary Table 4 | Summary of studies conducting pool boiling bubble dynamics analysis.

Supplementary Table 5 | Summary of analysis methods, types, and feature complexity from 2015 – 2022

Supplementary Table 6 | Literature summary of data stream analysis.

Supplementary Note 1. Pool boiling heat flux partitioning

Supplementary Note 2. Two-phase energy balance

Supplementary Note 3. Overview of forecasting models

Supplementary Table 1 | Literature summary of meta-analysis.

Objectives	AI Type	Year	Author	Application	Output
Meta-Analysis	MLP	2006	Ertunc ¹	Pool Boiling	CHF Prediction
	MLP, CF, RBF, GR	2017	Hassanpour ²	Pool Boiling	HTC Prediction
	Genetic Algorithm, ABC Algorithm, MLP, SVM	2019	Alic ³	Pool Boiling	Heat Flux Prediction
	MLP	2019	Gajghate ⁴	Pool Boiling	HTC Prediction
	MLP, RF	2021	Swartz ⁵	Pool Boiling	CHF Prediction
	MLP	2021	Liang ⁶	Pool Boiling	HTC and Surface Temperature Prediction
	DBN	2021	Kim ⁷	Pool Boiling	CHF Prediction
	MLP	2021	Calati ⁸	Pool Boiling	Nusselt Number and Heat Flux Prediction
	MLP	2021	Sajjad ⁹	Pool Boiling	HTC Prediction
	MLP	2021	McClure ¹⁰	Pool Boiling	Heat Flux Prediction
	MLP, RF, PINN	2021	Zhao ¹¹	Pool Boiling	CHF Prediction
	PINN	2022	Kim ¹²	Pool Boiling	Minimum Film Boiling Temperature
	SVM, RF, MLP	2022	Zhang ¹³	Pool Boiling	CHF Prediction
	MLP, RF	2018	Zhao ¹⁴	Flow Boiling	CHF Prediction
	MLP	2020	Qiu ¹⁵	Flow Boiling	HTC Prediction
	MLP	2021	Zhu ¹⁶	Flow Boiling, Flow Condensation	HTC Prediction
	MLP	2021	Lee ¹⁷	Flow Boiling	Pressure Drop Prediction
	MLP, XGBoost, GBM	2022	Kim ¹⁸	Flow Boiling	Nusselt Number Prediction
	RF,GBM, SVM, MLP	2022	Bard ¹⁹	Flow Boiling	HTC Prediction

Supplementary Table 1 | Literature summary of meta-analysis (continued).

Meta-Analysis	MLP, AdaBoost, RF	2020	Zhou ²⁰	Flow Condensation	HTC Prediction
	MLP	2020	Ewim ²¹	Tube Condensation	HTC Prediction
	MLP	2020	Longo ²²	Condensation	HTC Prediction
	SVM, RF, MLP	2021	Hughes ²³	Condensation	Pressure Drop and HTC Prediction
	MLP	2021	Yoo ²⁴	Condensation	HTC Prediction and Droplet Entrainment Rate
	FCM-ANFIS	2021	Mehrabi ²⁵	Condensation	HTC Prediction
	GBM	2021	Longo ²⁶	Boiling and Condensation	Pressure Drop Prediction
	MLP	2022	Cho ²⁷	Film Condensation	HTC Prediction
	CNN	2022	Lee ²⁸	Condensation	HTC Prediction

Supplementary Table 2 | Literature summary of physical feature extraction via ML.

Objectives	AI Type	Year	Author	Application	Output
Physical Feature Extraction	ANN	2019	Ravichandran ²⁹	Pool Boiling	Growth Time, Bubble Period, Nucleation Site Density
	CNN, MLP	2021	Suh ³⁰	Pool Boiling	Bubble Size, Bubble Count, Heat Flux Prediction
	CNN, RNN	2021	Rokoni ³¹	Pool Boiling	Departure Frequency, Bubble Size, Bubble Count
	CNN	2022	Suh ³²	Pool Boiling	Departure Diameter, Nucleation Site Density, Departure Frequency
	CNN	2022	Lee & Suh ³³	Pool Boiling	Departure Frequency, Nucleation Site Density, Departure Diameter
	CNN	2020	Cerqueira ³⁴	Bubbly Flows	Bubble Velocity, Size Distribution
	CNN	2020	Haas ³⁵	Bubbly Flows	Void Fraction
	CNN	2020	Torisaki ³⁶	Bubbly Flows	Void Fraction, Bubble Aspect Ratio
	CNN	2021	Kim ³⁷	Bubbly Flows	Bubble Detection, Shape Extraction
	CNN	2021	Li ³⁸	Bubbly Flows	Bubble Count, Bubble Size
	CNN	2021	Wang ³⁹	Bubbly Flows	Bubble Aspect Ratio, Bubble Size, Bubble Velocity
	CNN	2022	Hessenkemper ⁴⁰	Bubbly Flows	Bubble Size, Bubble Count
	CNN	2021	Suh ⁴¹	Dropwise Condensation	Droplet Growth Rate, Droplet Number Density, Local Heat Flux Mapping, Droplet Size Distribution
	CNN	2021	Yan ⁴²	Dropwise Condensation	Droplet Size, Droplet Number, Void Fraction

Supplementary Table 2 | Literature summary of physical feature extraction via ML (continued).

Physical Feature Extraction	CNN	2022	Khodakarami ⁴³	Pipewise Condensation	Droplet Shedding Frequency, Local Heat Flux Prediction
	CNN	2022	Ma ⁴⁴	Dropwise Condensation	Droplet Number Density, Droplet Size

Supplementary Table 3 | Literature summary of traditional computer vision methods.

Objectives	Approaches	Year	Author	Application	Output
Physical Feature Extraction (Traditional)	Thresholding	2002	Kulenovic ⁴⁵	Pool Boiling	Bubble Count, Departure Diameter
	Thresholding	2018	Surtaev ⁴⁶	Pool Boiling	Void Fraction
	Thresholding	2020	Serdyukov ⁴⁷	Pool Boiling	Departure Diameter, Void Fraction
	Thresholding	2002	Maurus ⁴⁸	Flow Boiling	Void Fraction, Bubble Density, Bubble Distance
	Thresholding	2021	Jin ⁴⁹	Film Boiling	Film Thickness
	Thresholding	2000	Maiti ⁵⁰	Dropwise Condensation	Surface Coverage, Droplet Size
	Thresholding	2014	Watanabe ⁵¹	Dropwise Condensation	Droplet Size Distribution, Surface Coverage
	Thresholding	2015	Wen ⁵²	Dropwise Condensation	Surface Coverage, Droplet Size, Droplet Size Distribution
	Circle Finder	2015	Castillo ⁵³	Dropwise Condensation	Number of Droplets, Droplet Growth Rate, Condensation Rate
	Thresholding	2017	Watanabe ⁵⁴	Dropwise Condensation	Droplet Size, Surface Coverage, Clustering Coefficient, Degree Distribution
	Thresholding	2017	Awlwazzan ⁵⁵	Dropwise Condensation	Droplet Size Distribution, Departure Diameter
	Thresholding	2018	Barati ⁵⁶	Dropwise Condensation	Probability density function, Surface Coverage
	Circle Finder	2019	Wikramanayake ⁵⁷	Dropwise Condensation	Droplet Size, Droplet Count
	Circle Finder	2019	Castillo ⁵⁸	Dropwise Condensation	Nearest Neighbor Analysis, Condensation Rate, Intensity of Interaction
	Thresholding	2019	Haque ⁵⁹	Dropwise Condensation	Droplet Size, Droplet Density, Surface Coverage

Supplementary Table 3 | Literature summary of traditional computer vision methods (continued).

Physical Feature Extraction (Traditional)	Thresholding	2020	Parin ⁶⁰	Dropwise Condensation	Surface Coverage, Droplet Size, Droplet Size Distribution
	Thresholding	2020	Chung ⁶¹	Dropwise Condensation	Surface Coverage
	Thresholding	2021	Bonab ⁶²	Dropwise Condensation	Number of Droplets, Droplet Size
	Thresholding	2021	Haque ⁶³	Dropwise Condensation	Droplet Size, Droplet Density, Surface Coverage
	Thresholding	2022	Damoulakis ⁶⁴	Dropwise Condensation	Droplet Count, Area Coverage, HTC Prediction

Supplementary Table 4 | Summary of studies conducting pool boiling bubble dynamics analysis.

Year	Application	Author	Material	Studied q'' Range (W/cm ²)
2004	Pool Boiling	Chatpun ⁶⁵	Si	3-6
2014		Dong ⁶⁶	Si	2-21
2016		Kim ⁶⁷	Si	20-60
2015		Thiagarajan ⁶⁸	Cu	2.5-42
2019		Zhou ⁶⁹	Cu	8-11
2019		Chang ⁷⁰	Cu	2-56
2020		Zhao ⁷¹	Cu	4-70

Supplementary Table 5 | Summary of analysis methods, types, and feature complexity from 2015 – 2022.

Year	Application	Author	Analysis Type	Feature Complexity		
				Spatial	STG	STI
2015	Boiling	Hamzekhani ⁷²	Decoupled	M		M
2015		Lioumbas ⁷³	Statistics Only	TCV	TCV	
2015		Thiagarajan ⁶⁸	Coupled	M		M
2016		Hsu ⁷⁴	Decoupled	M		
2016		Dinesh ⁷⁵	Decoupled	M	M	M
2016		Yoo ⁷⁶	Decoupled	M	M	M
2016		Guan ⁷⁷	Decoupled	TCV		
2016		Kim ⁶⁷	Coupled	TCV	TCV	
2017		Kumar ⁷⁸	Decoupled	M		
2017		Walunj ⁷⁹	Decoupled	TCV		M
2017		Wang ⁸⁰	Decoupled	M		M
2018		Surtaev ⁴⁶	Statistics Only	TCV	TCV	TCV
2018		Pranoto ⁸¹	Decoupled	M		M
2018		ALIÇ ⁸²	Decoupled	TCV		
2018		Vlachou ⁸³	Decoupled	M	M	
2018		Zhou ⁸⁴	Decoupled	M		
2019		Ravichandran ²⁹	Coupled			DL
2019		Zhao ⁸⁵	Decoupled	M	M	M
2019		Hasan ⁸⁶	Decoupled	M		
2019		Bhavnani ⁸⁷	Decoupled	TCV		TCV
2019		Chang ⁸⁸	Coupled	M		M
2020		Serdyukov ⁴⁷	Decoupled	TCV	TCV	TCV
2020		Cheng ⁸⁹	Decoupled	M		M
2020		Mehdi ⁹⁰	Decoupled	M	M	M
2020		Gatapova ⁹¹	Decoupled	TCV	TCV	
2020		Kim ⁹²	Coupled	TCV	TCV	
2020		Zhou ⁶⁹	Decoupled	M		M
2021		Suh ³⁰	Decoupled	DL		
2021		Rokoni ³¹	Decoupled	DL		

Supplementary Table 5 | Summary of analysis methods, types, and feature complexity from 2015 – 2022 (continued).

Year	Application	Author	Analysis Type	Feature Complexity		
				Spatial	STG	STI
2021	Boiling	Hua ⁹³	Statistics Only	TCV	TCV	
2022		Lee, Suh ⁹⁴	Statistics Only	DL		DL
2022		Shah ⁹⁵	Decoupled	M	M	M
2022		Li ⁹⁶	Decoupled	M		M
2022		Wang ⁹⁷	Decoupled	M		M
2015	Condensation	Hou ⁹⁸	Decoupled	M	M	
2015		Wen ⁵²	Statistics Only	TCV	TCV	
2015		Peng ⁹⁹	Decoupled	M		
2015		Castillo ⁵³	Statistics Only	TCV	TCV	TCV
2015		Chen ¹⁰⁰	Statistics Only	M	M	
2015		Mei ¹⁰¹	Statistics Only	M		
2015		Zhu ¹⁰²	Decoupled	M	M	
2015		Zhao ¹⁰³	Decoupled	M	M	
2015		Sun ¹⁰⁴	Statistics Only			M
2017		Watanabe ⁵⁴	Decoupled	TCV	TCV	
2017		Alwazzan ⁵⁵	Statistics Only	TCV		
2017		Weisensee ¹⁰⁵	Coupled	M		
2017		Sharma ¹⁰⁶	Statistics Only			M
2017		Al-Khayat ¹⁰⁷	Statistics Only	M	M	
2017		Cha ¹⁰⁸	Statistics Only	M		
2017		Wang ¹⁰⁹	Statistics Only	M	M	
2017		Lu ¹¹⁰	Decoupled	M		
2018		Zheng ¹¹¹	Decoupled	M		
2018		Barati ⁵⁶	Coupled	TCV	TCV	
2018		Dong ¹¹²	Statistics Only	M		
2018		Zhao ¹¹³	Statistics Only	M	M	
2019		Wikramanayake ⁵⁷	Statistics Only	TCV		
2019		Orejon ¹¹⁴	Statistics Only	TCV	TCV	
2019		Ji ¹¹⁵	Decoupled	M		

Supplementary Table 5 | Summary of analysis methods, types, and feature complexity from 2015 – 2022 (continued).

Year	Application	Author	Analysis Type	Feature Complexity		
				Spatial	STG	STI
2019	Condensation	Castillo ⁵⁸	Statistics Only	TCV	TCV	TCV
2019		Jiang ¹¹⁶	Statistics Only	M	M	
2019		Lo ¹¹⁷	Decoupled	M		
2019		Han ¹¹⁸	Statistics Only	TCV	TCV	
2019		Wang ¹¹⁹	Statistics Only	M	M	
2019		Haque ¹²⁰	Statistics Only	TCV	TCV	
2019		Wang ¹²¹	Statistics Only	M	M	
2019		Vandadi ¹²²	Statistics Only	M	M	
2019		Chen ¹²³	Statistics Only	M	M	
2020		Parin ⁶⁰	Decoupled	TCV	TCV	
2020		Cha ¹²⁴	Decoupled	M		
2020		Song ¹²⁵	Coupled			M
2020		Wang ¹²⁶	Decoupled	M		
2020		Chung ⁶¹	Statistics Only	TCV	TCV	
2020		Gulfam ¹²⁷	Statistics Only	M		
2021		Suh ⁴¹	Coupled	DL	DL	DL
2021		Yan ⁴²	Statistics Only	DL	DL	
2021		Wang ¹²⁸	Decoupled	M		
2021		Bonab ⁶²	Decoupled	TCV		
2021		Wang ¹²⁹	Decoupled	M		
2021		Cheng ¹³⁰	Statistics Only			M
2021		Haque ⁶³	Statistics Only	TCV	TCV	
2021		Tripathy ¹³¹	Decoupled	M		
2021		Baba ¹³²	Statistics Only	M	M	M
2021		Xiao ¹³³	Statistics Only	TCV	TCV	
2022		Khodakarami ⁴³	Coupled	DL	DL	
2022		Ma ⁴⁴	Decoupled	DL	DL	
2022		Damoulakis ⁶⁴	Decoupled	DL		
2022		Chang ¹³⁴	Decoupled	M		

2022		Deng ¹³⁵	Decoupled	M	M	
2022		Pathak ¹³⁶	Statistics Only	TCV	TCV	
2022		Lee ¹³⁷	Coupled	TCV	TCV	M

TCV, traditional computer vision; M, manual; DL, deep learning

Supplementary Table 6 | Literature summary of data stream analysis.

No.	Objectives	AI Type	Year	Author	Application	Output
1	Multiphase Pattern Identification	CNN, MLP	2021	Suh ³⁰	Pool Boiling	Heat Flux Prediction
2		CNN	2021	Rassoulinejad-Mousavi ¹³⁸	Pool Boiling	CHF Detection
3		SVM, MLP	2017	Hobold ¹³⁹	Pool Boiling	Boiling Regime Classification
4		CNN, MLP	2018	Hobold ¹⁴⁰	Pool Boiling	Heat Flux Prediction
5		CNN	2018	Hobold ¹⁴¹	Pool Boiling	CHF Detection
6		CNN	2021	Sinha ¹⁴²	Pool Boiling	CHF Detection
7		CNN, MLP	2021	Seal ¹⁴³	Pipewise Condensation	Flow Regime Classification
8		CNN	2022	Nie ¹⁴⁴	Flow Boiling	Flow Regime Classification
9		CNN	2020	Yuan ¹⁴⁵	Condensation	Droplet Jumping Direction
10		CNN, RNN	2022	Kadish ¹⁴⁶	Two-phase Flow	Vapor Quality, Flow Regime Classification
11		CNN, LSTM, CNN-LSTM	2022	Dale ¹⁴⁷	Pool Boiling	CHF Detection
12		SVM	2005	Qi ¹⁴⁸	Two-phase Flow	Flow Regime Classification
13		SVM	2009	Wang ¹⁴⁹	Two-phase Flow	Flow Regime Classification
14		SVM	2008	Zhou ¹⁵⁰	Two-phase Flow	Flow Regime Classification
15		SVM	2020	Zhang ¹⁵¹	Two-phase Flow	Flow Regime Classification
16		ANN	2021	Haase ¹⁵²	Two-phase Flow	Flow Regime Classification
17		CNN-SVM	2022	Xu ¹⁵³	Two-phase Flow	Flow Regime Classification
18		CNN	2022	Dai ¹⁵⁴	Condensation	Energy Conversion Efficiency
19		SVM	2022	dos Santos Ambrosio ¹⁵⁵	Two-phase Flow	Flow Regime Classification
20		CNN, RNN	2021	Rokoni ³¹	Pool Boiling	Bubble Morphology Forecast
21		ANN	2021	Ueki ¹⁵⁶	Pool Boiling	ONB Detection

Supplementary Table 6 | Literature summary of ML under challenge 3.

No.	Objectives	AI Type	Year	Author	Application	Output
1	Multiphase Pattern Identification	SVM, MLP	2017	Hobold ¹³⁹	Pool Boiling	Boiling Regime Classification
2		CNN, MLP	2018	Hobold ¹⁴⁰	Pool Boiling	Heat Flux Prediction
3		CNN	2018	Hobold ¹⁴¹	Pool Boiling	CHF Detection
4		CNN, MLP	2021	Suh ³⁰	Pool Boiling	Heat Flux Prediction
5		CNN	2021	Rassoulinejad-Mousavi ¹³⁸	Pool Boiling	CHF Detection
6		CNN	2021	Sinha ¹⁴²	Pool Boiling	CHF Detection
7		CNN, RNN	2021	Rokoni ³¹	Pool Boiling	Bubble Morphology Forecast
8		ANN	2021	Ueki ¹⁵⁶	Pool Boiling	ONB Detection
9		CNN, LSTM, CNN-LSTM	2022	Dale	Pool Boiling	CHF Detection
10		CNN	2022	Nie ¹⁴⁴	Flow Boiling	Flow Regime Classification
11		SVM	2005	Qi ¹⁴⁸	Two-phase Flow	Flow Regime Classification
12		SVM	2008	Zhou ¹⁵⁰	Two-phase Flow	Flow Regime Classification
13		SVM	2009	Wang ¹⁴⁹	Two-phase Flow	Flow Regime Classification
14		SVM	2020	Zhang ¹⁵¹	Two-phase Flow	Flow Regime Classification
15		ANN	2021	Haase ¹⁵²	Two-phase Flow	Flow Regime Classification
16		CNN-SVM	2022	Xu ¹⁵³	Two-phase Flow	Flow Regime Classification
17		CNN, RNN	2022	Kadish ¹⁴⁶	Two-phase Flow	Vapor Quality, Flow Regime Classification
18		SVM	2022	dos Santos Ambrosio ¹⁵⁵	Two-phase Flow	Flow Regime Classification
19		CNN	2020	Yuan ¹⁴⁵	Condensation	Droplet Jumping Direction
20		CNN, MLP	2021	Seal ¹⁴³	Pipewise Condensation	Flow Regime Classification
21		CNN	2022	Dai ¹⁵⁴	Condensation	Energy Conversion Efficiency

Supplementary Note 1. Pool boiling heat flux partitioning

The boiling heat flux released from the surface q_{tot}'' is partitioned by the three principle components, namely, natural convection q_{nc}'' outside of the area of influence A_{inf} , transient conduction q_{tc}'' over the bubble-influenced area, and evaporative heat transfer q_{ev}'' during phase change as follows:¹⁵⁷⁻¹⁶⁵

$$q_{tot}'' = q_{nc}'' + q_{fc}'' + q_{ev}'' \quad (1)$$

$$q_{nc}'' = \left(1 - N_b \frac{\pi D_b^2}{4}\right) h_c \Delta T \quad (2)$$

$$q_{tc}'' = \frac{1}{2} [D_b^2 N_b (\sqrt{\pi k \rho c f_b})] \Delta T \quad (3)$$

$$q_{ev}'' = N_b f_b \left(\frac{\pi}{6} D_b^3\right) \rho_v h_{fg} \quad (4)$$

where N_b is the effective nucleation site density, h_c is the average heat transfer coefficient (HTC) outside of the A_{inf} , D_b is the departure diameter, ΔT is the temperature difference between the surface and medium, and ρ is the density of the liquid, c is the heat capacity, f_b is the departure frequency, and h_{fg} is the latent heat of evaporation.

Supplementary Note 2. Two-phase energy balance

Heat transfer rate. According to the conservation of energy requirements, the rate of the heat transfer into the surface must equal the rate of energy release due to condensation at the interface:

$$q = \dot{m}_c h_{fg} = \rho_w V F h_{fg} \quad (5)$$

where $\dot{m}_c$ is the condensate mass flux, ρ_w is the condensate density, V is average shedding droplet volume, F is the droplet shedding frequency, and h_{fg} is the latent heat of vapor-to-liquid phase change. By having access to individual pixel-based droplet features throughout time, Eq. 5 can be expressed to calculate the heat transfer per individual droplet:

$$q_i^j = \dot{m}_i h_{fg} = \pi \rho_w h_{fg} (1 - \cos \theta_a)^2 (2 + \cos \theta_a) r_i^{j2} \frac{dr_i^j}{dt} \quad (6)$$

where r_i is the individual droplet radius, dr_i/dt is the individual droplet growth rate, and θ_a is the apparent advancing contact angle.

Supplementary Note 3. Overview of forecasting models

As a brief overview, RNNs and long short term memory (LSTM) networks are the most popular models used for sequence modeling due to their ability to retain past information when processing the current time step information.^{166,167} However, training RNNs and LSTMs has proved to be problematic due to vanishing or exploding gradients when dealing with long sequences.¹⁶⁸ Meanwhile, CNNs have also been used for forecasting problems as well,¹⁶⁹ despite them having no recurrent connections (i.e., time-invariant). The time-invariance of CNNs allow them to be computationally more economic than RNNs by being able to learn from parallel batches (i.e., parallelization).¹⁷⁰ Furthermore, CNNs can sometimes look at data from a broader perspective than RNNs because they do not rely on previous timesteps to make predictions.¹⁷¹ Hybrid models such as the CNN-LSTM and ConvLSTM have also been proposed for spatio-temporal predictions.^{172,173} Amid new advances in computer science, a surge of recent studies have suggested that transformers may be a promising solution to address some of the disadvantages of RNN- and CNN-based models.^{167,174} Transformers utilize attention mechanisms that can access all previous states and differentially weight them based on their contextual relevance.¹⁷⁴ By using these attention mechanisms, transformers can look back very far into past timesteps and their calculations can be performed in parallel.¹⁷⁴ Whichever model is chosen in this respect, the fundamental forecasting problem eventually revolves around the quality and quantity of the data, the complexity and heterogeneity of the observed phenomena, and the timeliness of predictions.^{175,176}

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