Tianjin University

13TH CIMAC CASCADES

Enhancing PEMFC Efficiency: A Dual Approach Using PCMs and ANN Modeling

Iman Sarani

2024.08.15

Qingdao, China

Contents

Research significance

Future of transportation

In recent years, various green vehicle technologies are growing, and consumers are choosing among them based on their preferences

Fuel cell vehicles

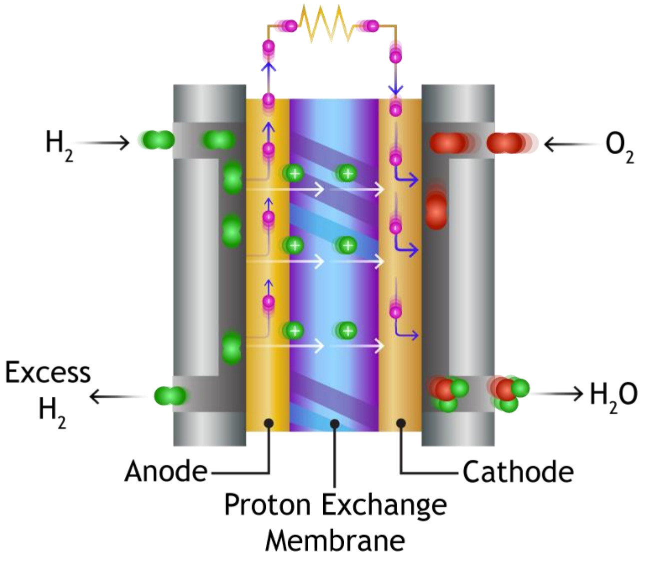
The projected market size of hydrogen fuel cells from 2020 to 2030, showing a significant increase from $1.2 billion in 2020 to $131.06 billion in 2030.

Hydrogen Fuel Cells Market Size, 2020 to 2030 (USD Billion)

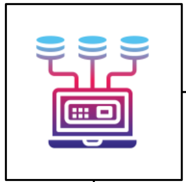
Background

How PEMFC Works

Electricity generation occurs through the electrochemical reaction of hydrogen and oxygen, producing water vapor as a byproduct.



Segments

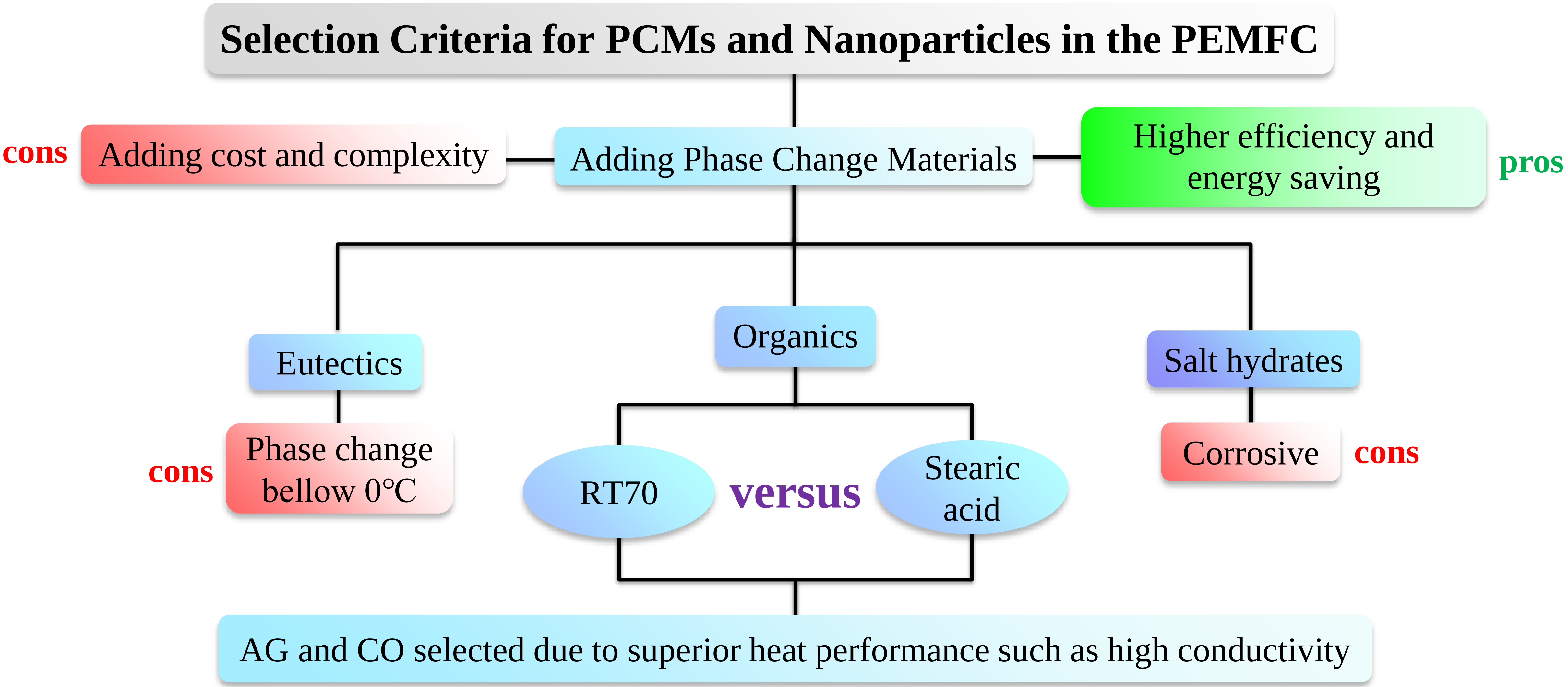


Numerical → Numerical segment explores using hybrid nano-composite phase change materials (HNCPCMs) to cool proton exchange membrane fuel cells (PEMFCs) during operation.

Experimental → Experimental segment explores insulation and PCMs for maintaining PEMFC temperature and evaluates RSM versus ANN in performance modeling and optimization.

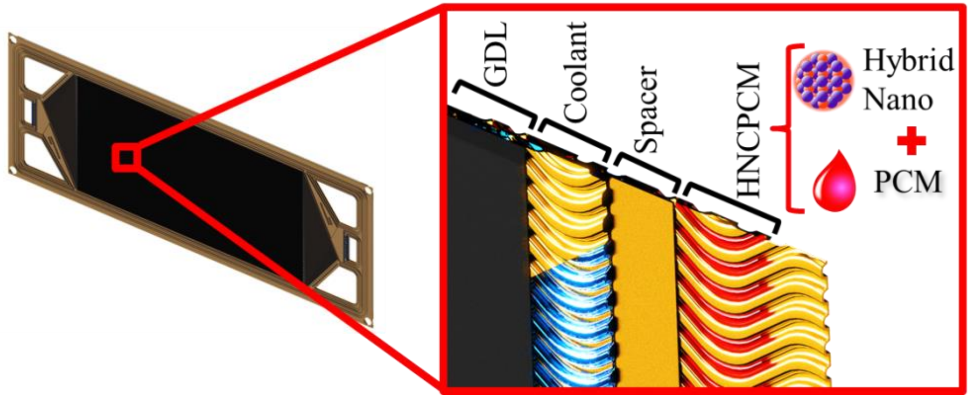
Contents

Numerical model



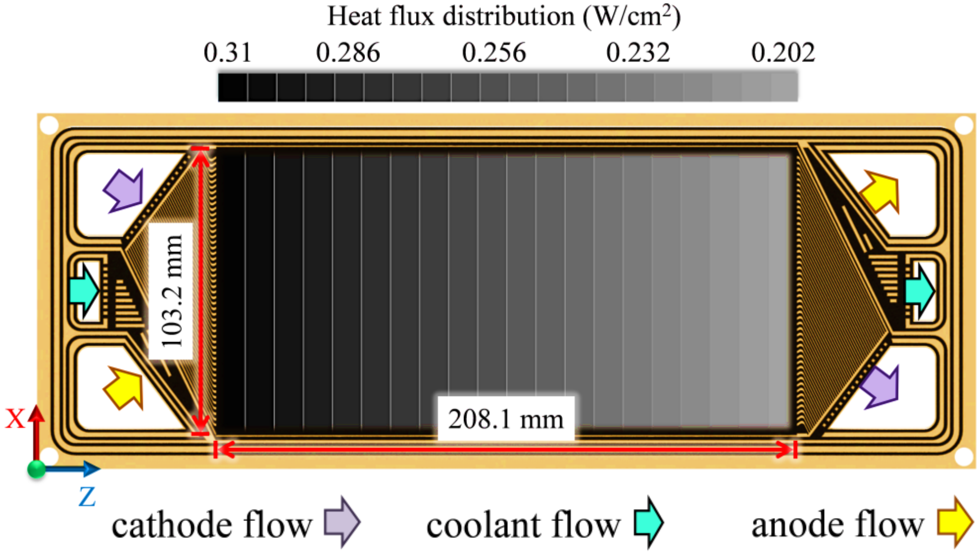
Numerical model

Computational domain



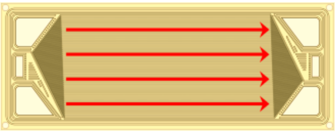
Waste heat generated: $Q = P_{out} ? \left(\frac{1.25}{V} \quad 1 \right)$

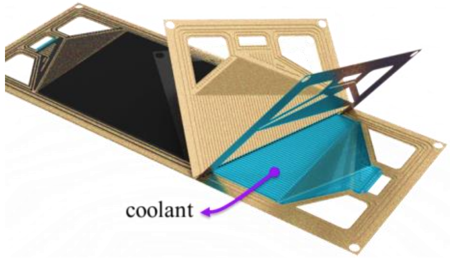
Heat flux distribution



Model A

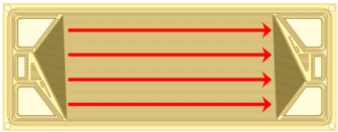
Straight BP

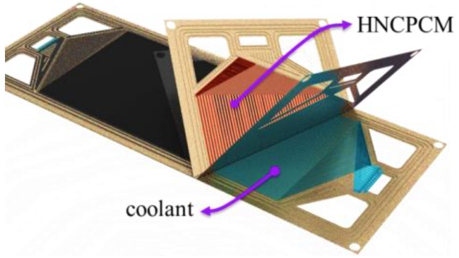




Model B

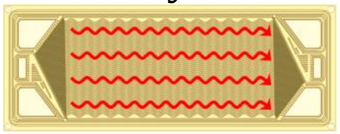
HNCPCM + Straight BP

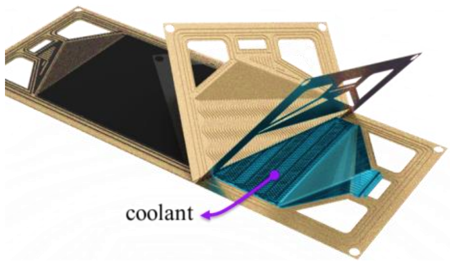




Model C

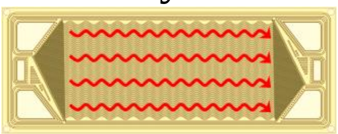
Wavy BP

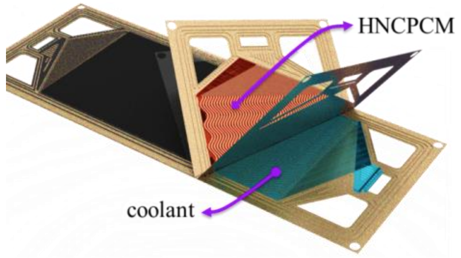




Model D

HNCPCM + Wavy BP





Contents

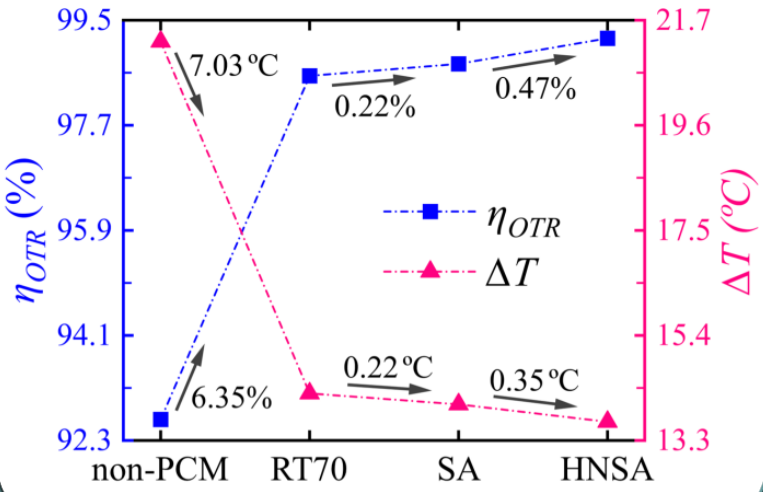
Numerical model results

Liquid cooling system off

Evaluating various PCM materials

Thermal efficiency:

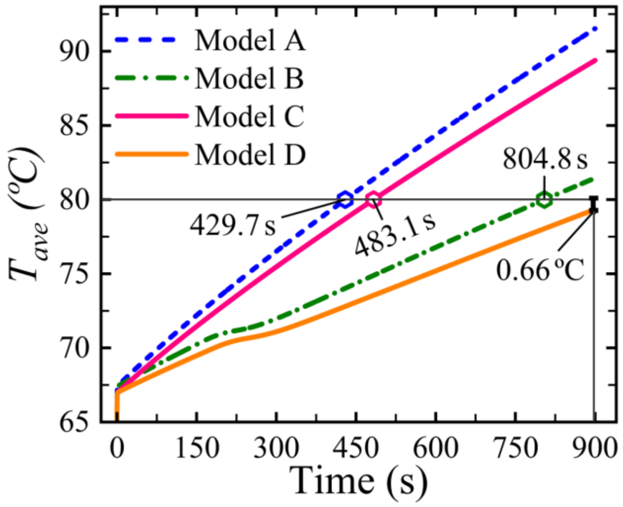
$$\eta_{OTR} = \left(1 - \frac{|T_{ave} - T_{OTR}|}{T_{opt}}\right) \times 100$$



1

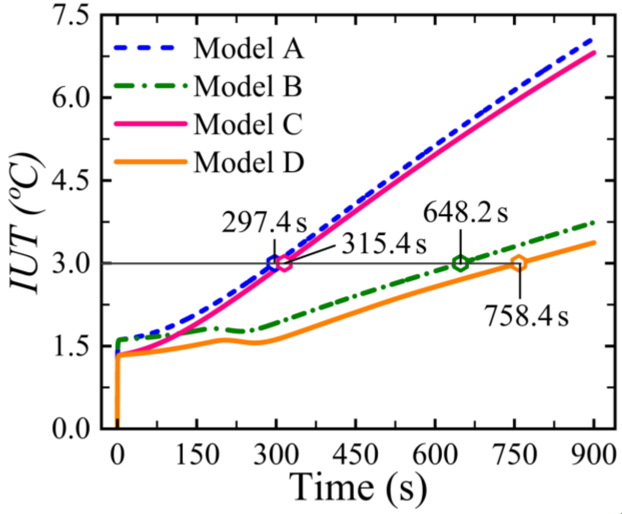
Evaluating various configurations

2

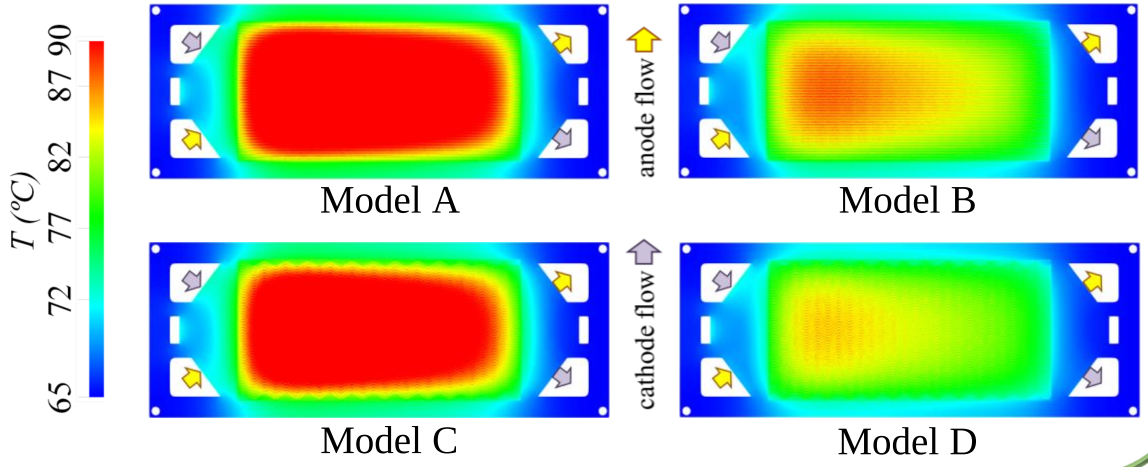


Temperature uniformity

3



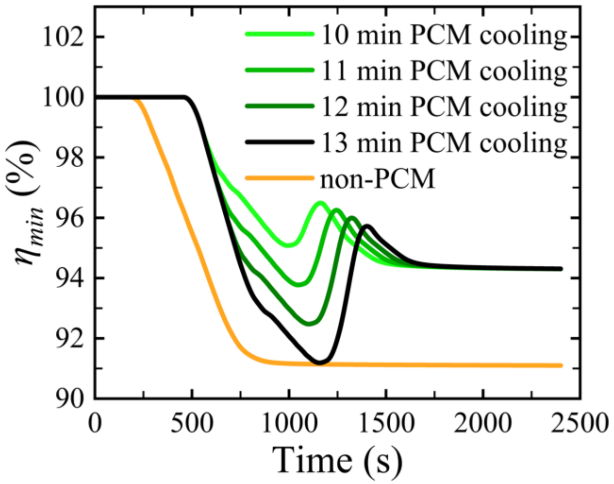
Temperature contours of different models at 15th min



Numerical model results

Liquid cooling system on

Evaluating the appropriate time of turning-on the cooling system



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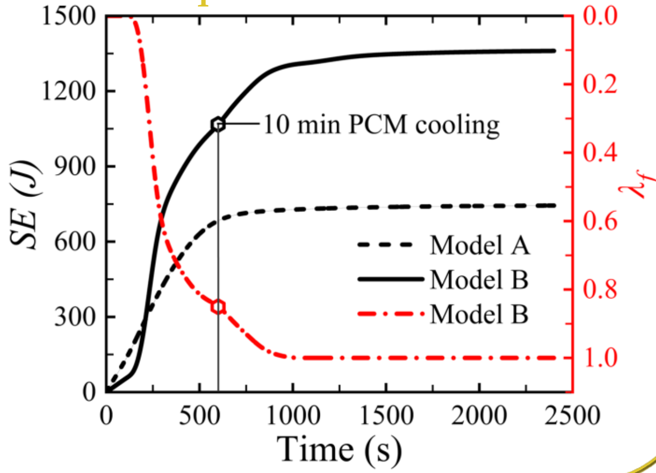
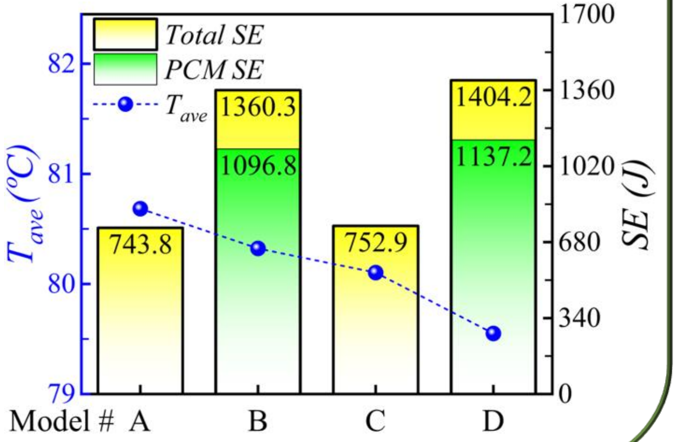
Transient energy storage and liquid fraction

2

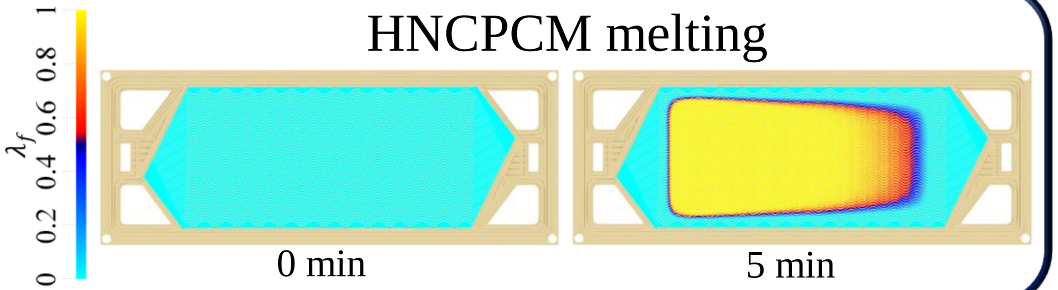


Stored energy in different models after 40 minutes

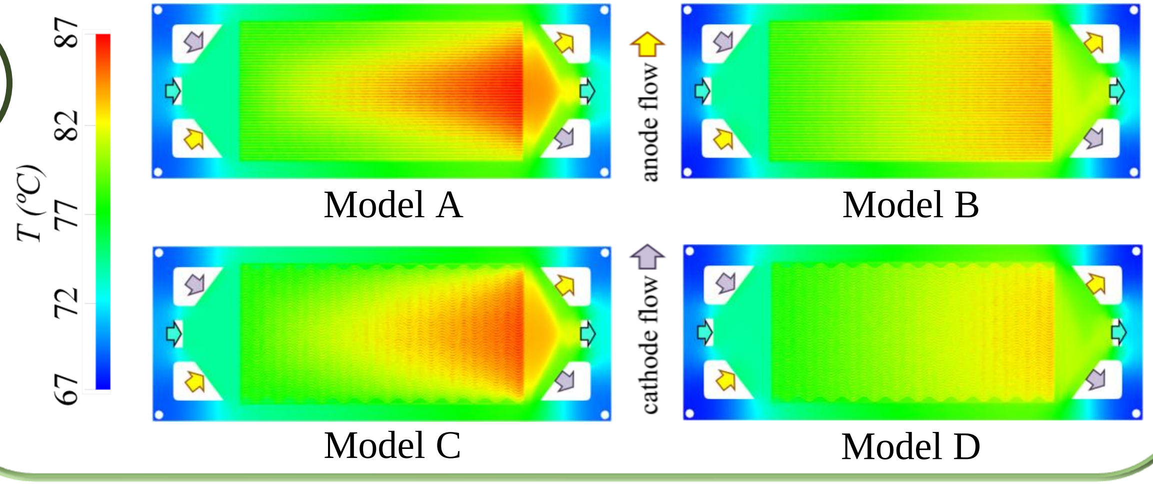
3



HNCPCM melting



Temperature contours of different models at 40th min



Contents

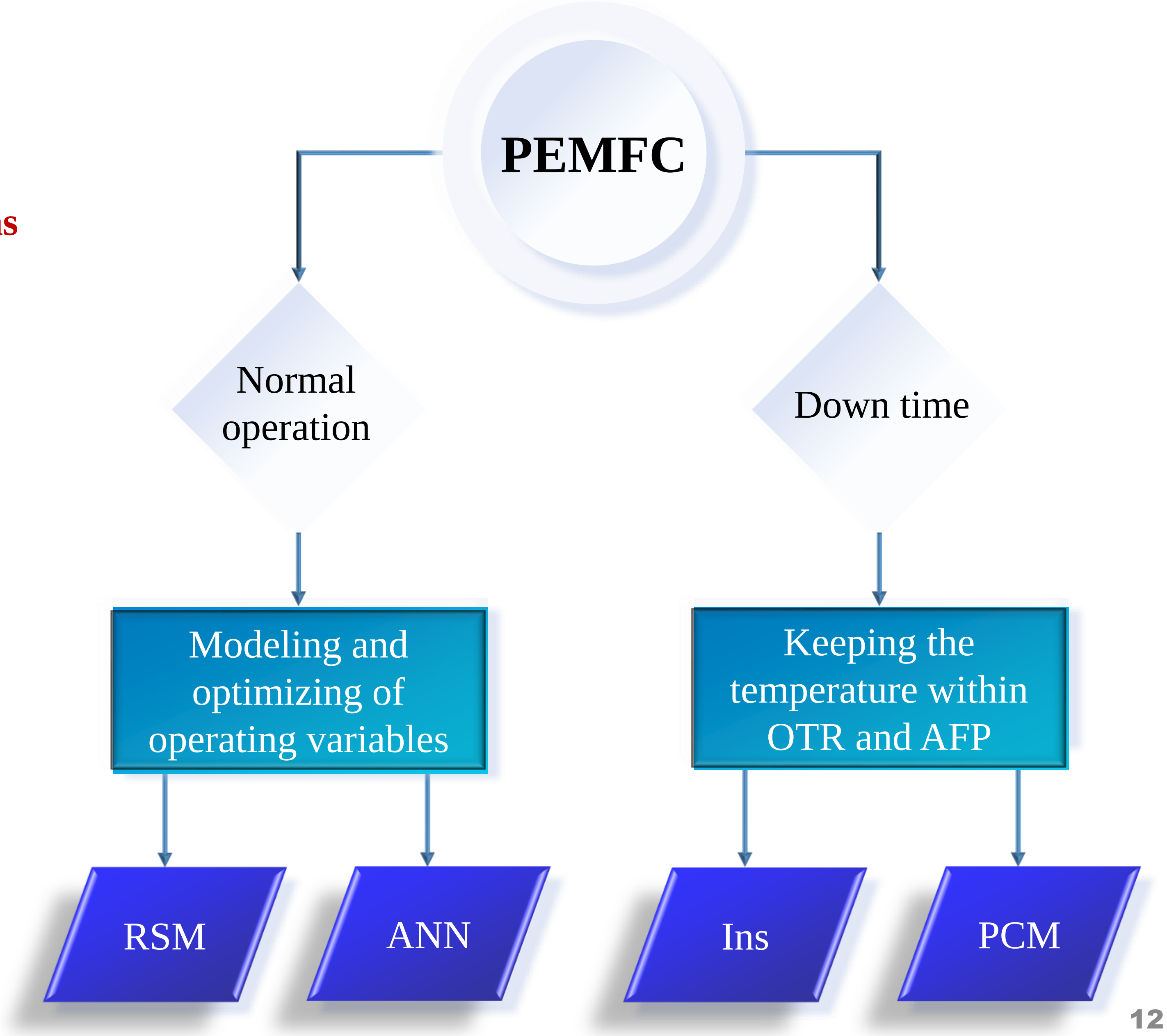
Experimental segment

➢ **Optimizing performance under operating conditions**

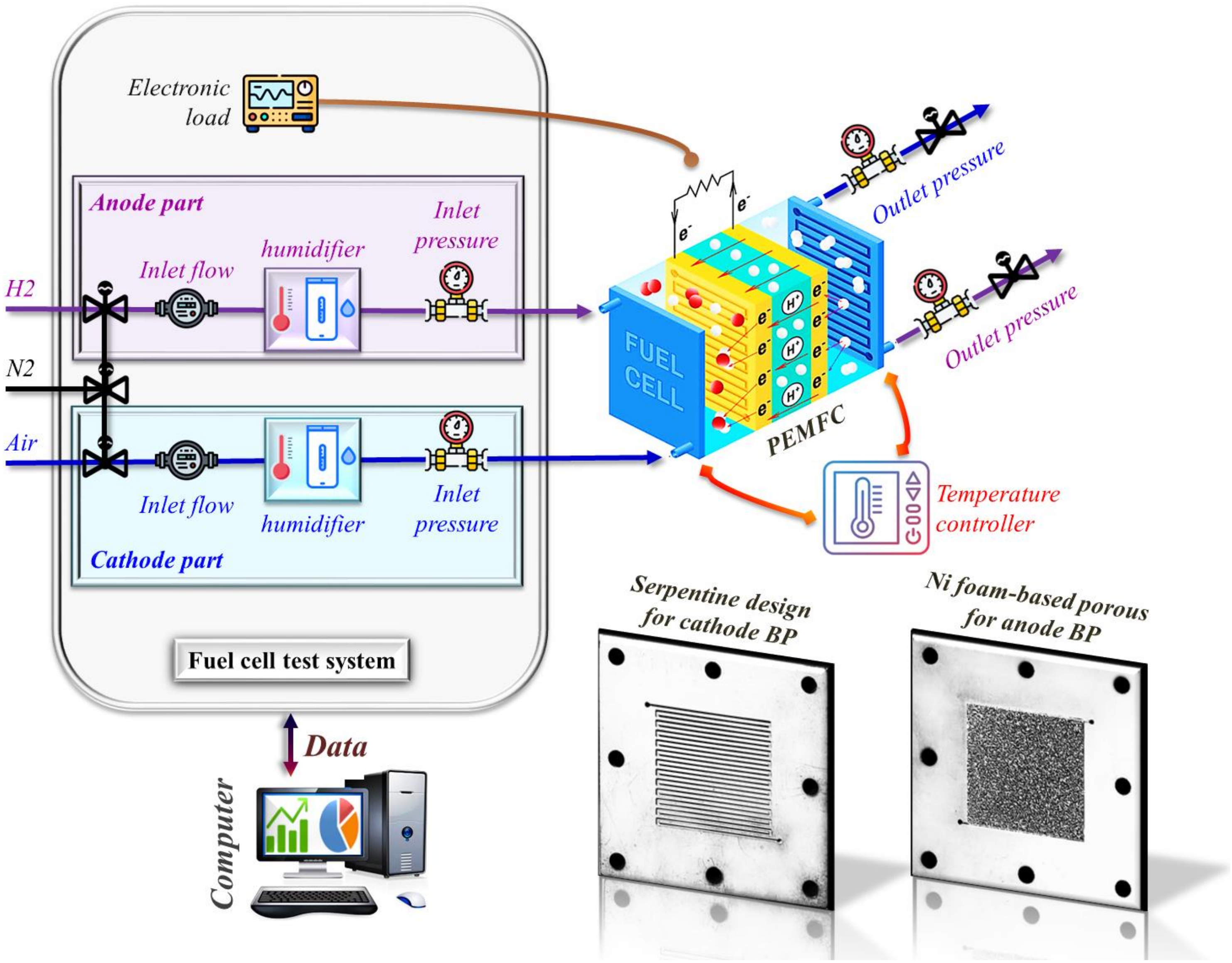
✓ Comparative analysis of Response Surface Methodology (RSM) Artificial Neural Networks (ANN) Aims to predicting performance of PEMFC

➢ **Maintaining functionality during downtime**

✓ Use of Phase Change Materials (PCMs) to Maintaining temperature within Operating Temperature Range (OTR) and Above Freezing Point (AFP)



Experimental model



PEMFC testing setup

❖ **Main components**

- Fuel cell testing station with programmable electronic load
- Gas supply systems for hydrogen (anode) and air (cathode)
- Humidification systems for proper membrane moisture
- Temperature control system
- Data acquisition system (DAQ)

❖ **Key features**

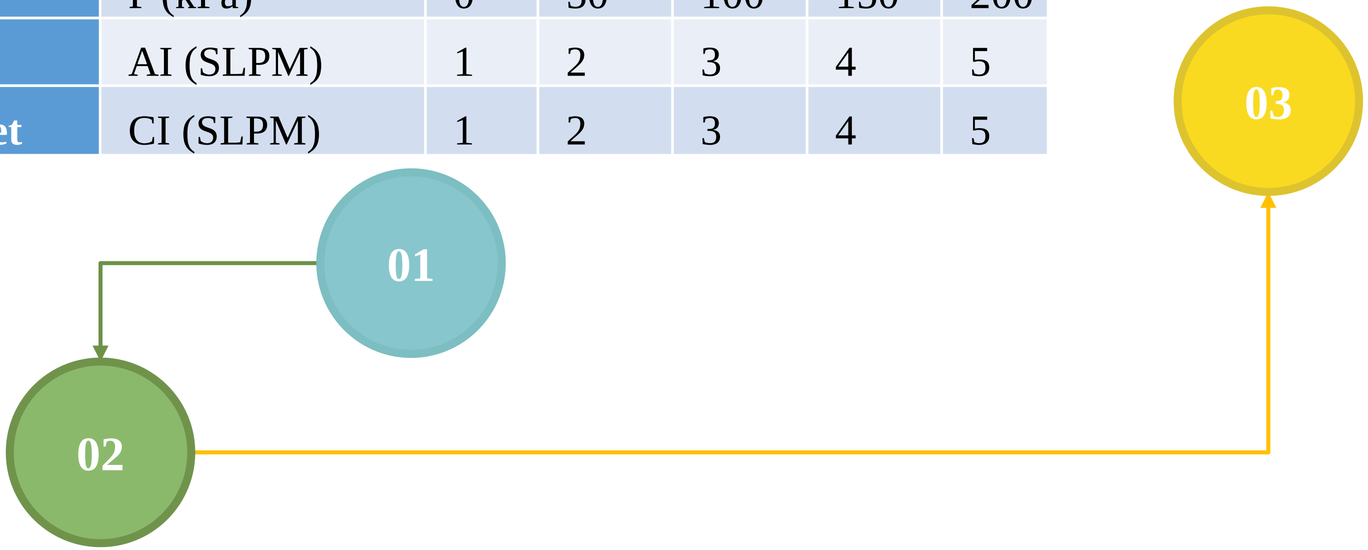
- Electronic load sets voltage to 0.6 V and measures current
- Mass flow controllers for precise gas delivery
- Thermal management with heating elements, cooling fans, and thermocouples
- Real-time monitoring and data collection

Experimental model

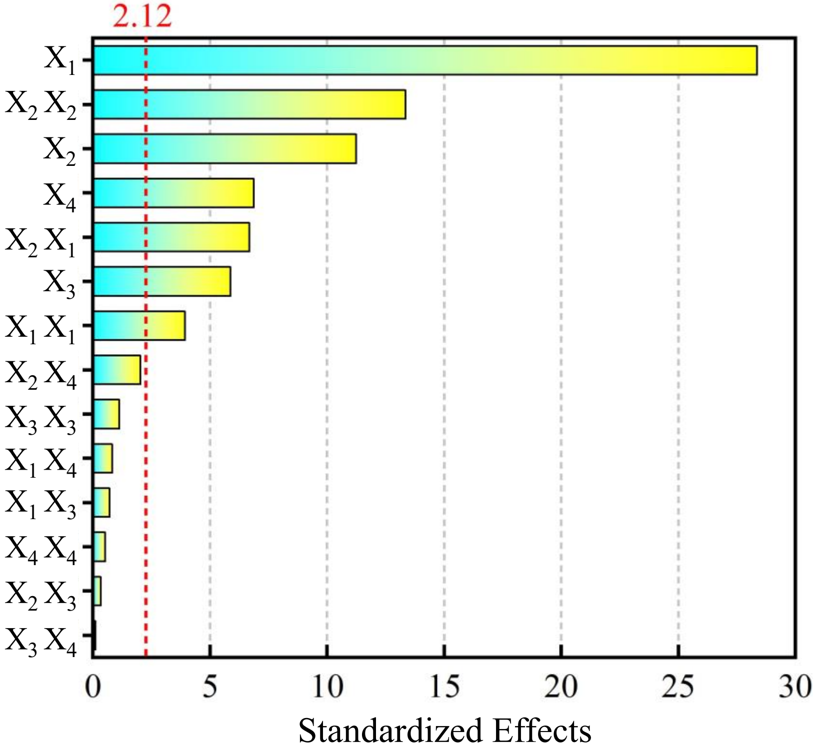
RSM Modeling for PEMFC Power Density Prediction

Factors and Their Corresponding Levels for the Experiment.

Variables	Symbol	Ranges and levels				
		- α	-1	0	+1	+ α
Temperature	T (℃)	50	60	70	80	90
Pressure	P (kPa)	0	50	100	150	200
Anode inlet	AI (SLPM)	1	2	3	4	5
Cathode inlet	CI (SLPM)	1	2	3	4	5



- The Pareto chart ranks the absolute values of the effects from largest to smallest.



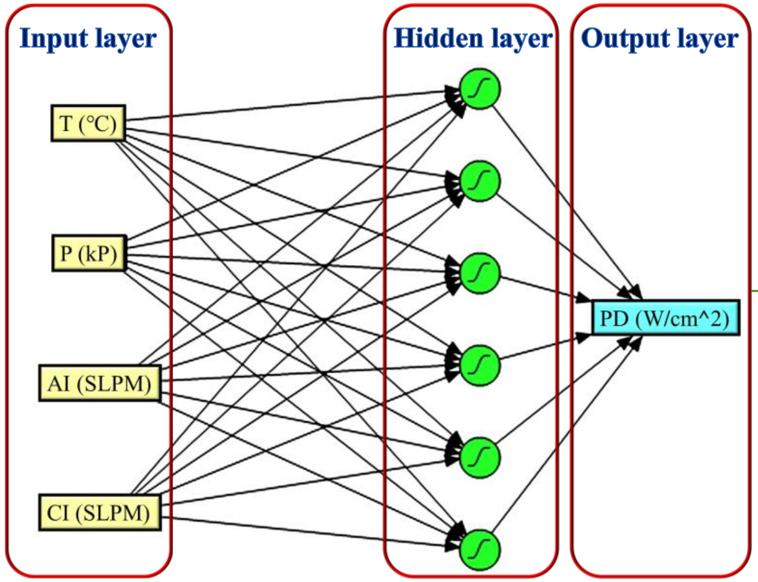
- **The regression equation:**

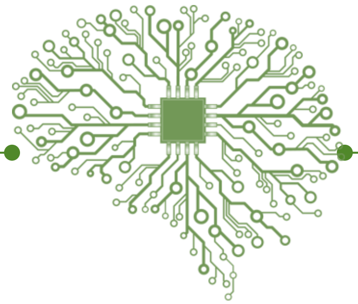
$$Y = -2.987 + 0.10002\ X1 - 0.00162\ X2 + 0.0716\ X3 + 0.1599\ X4 - 0.000701\ X1 \times X1 - 0.000008\ X2 \times X2 - 0.00580\ X3 \times X3 - 0.00270\ X4 \times X4 + 0.000094\ X1 \times X2 - 0.000200\ X1 \times X3 - 0.001396\ X1 \times X4 + 0.000100\ X2 \times X3 - 0.000109\ X2 \times X4 + 0.00034\ X3 \times X4$$

Experimental model

ANN Modeling for PEMFC Power Density Prediction

- The model architecture consists of six neurons; and an output layer with a single neuron representing the predicted power density (PD).





Matrices of weights

W1: weights between the input and the hidden layers; **W2:** weights between the hidden and the output layers.

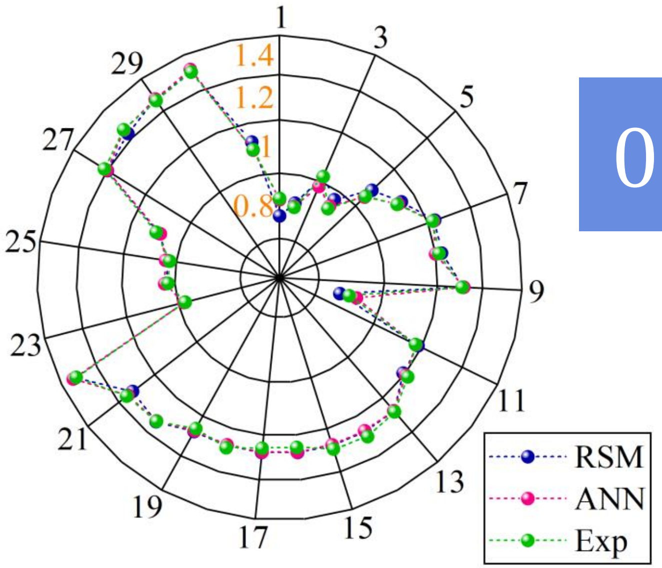
Neuron	W1				Bias	W2	
	T	P	AI	CI		Neuron	Weight
1	-0.0351	0.0109	-0.2492	0.007	2.3	1	0.8974
2	-0.0146	-0.0015	-0.1102	-0.0814	1.7619	2	-0.2631
3	0.09435	-0.0041	-0.1411	0.1328	-6.5948	3	-0.8993
4	-0.0053	0.0013	0.0274	0.2505	-0.6439	4	0.3496
5	-0.092	0.0047	-0.0802	-0.0428	5.8985	5	-1.4168
6	-0.003	0.0018	-0.0844	-0.0146	0.3135	6	-0.4144
						Bias	0.6892

Contents

Experimental model results

Comparison of RSM and ANN Models for Predicting Power Density

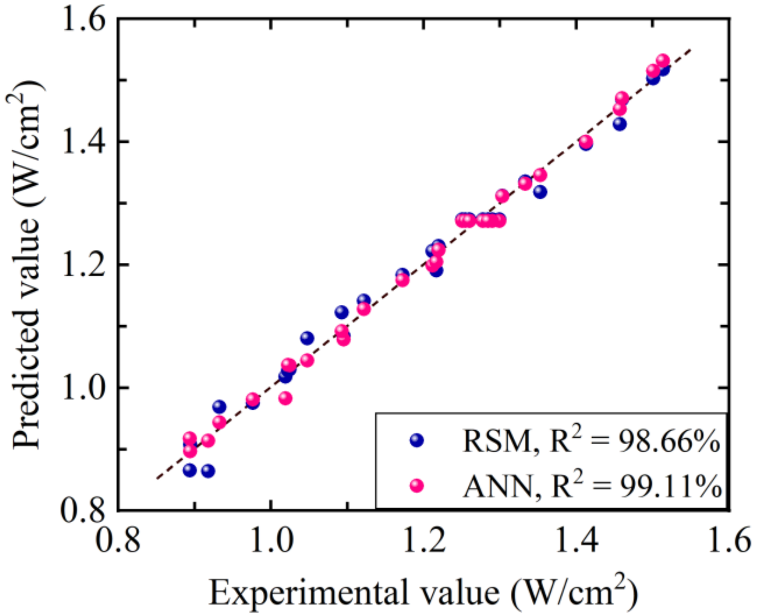
Radar chart across the 31 runs



01

02

Scatter plot of predicted vs experimental PD values



03

Comparative error analysis of RSM and ANN

Error	RSM	ANN
Correlation coefficient (R^2)	0.986	0.991
Root mean square error (RMSE)	0.021	0.014
Standard error of prediction (SEP %)	1.731	1.186
Average absolute deviation (AAD %)	1.466	0.992

04

Optimal values for the maximum power density.

T	P	AI	CI	PD		
				Exp.	CCD	ANN
79.1	200	5	5	1.71	1.68	1.73

Experimental model results

Fuel Cell Performance Factors

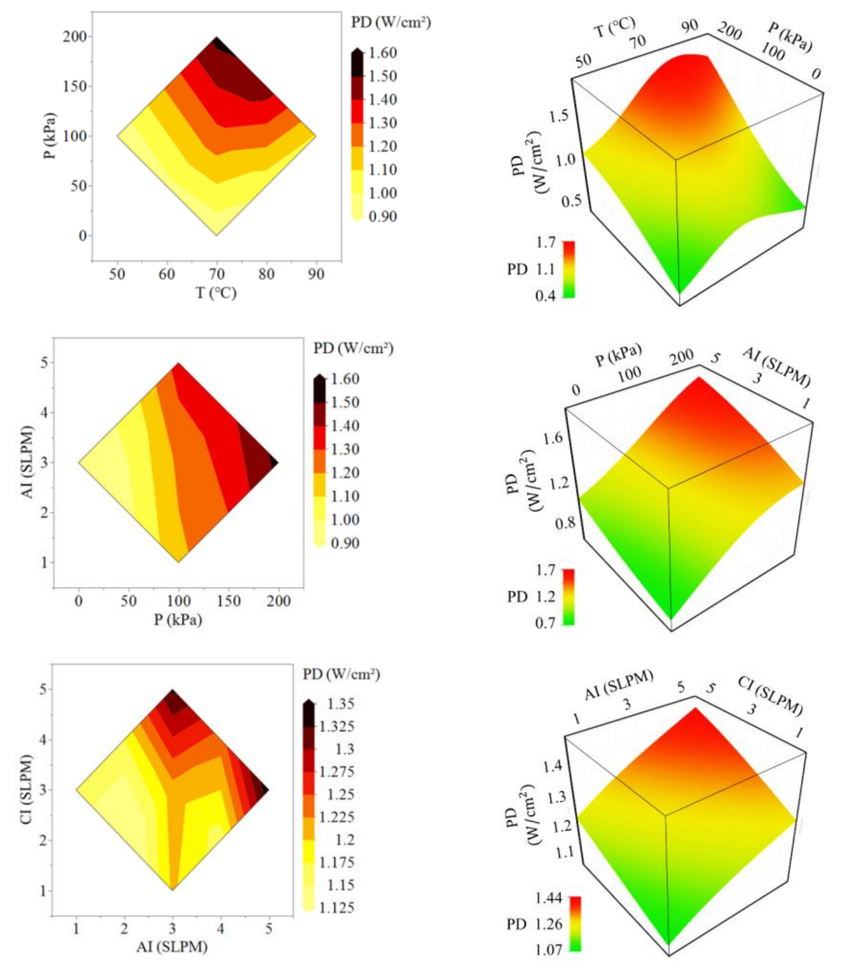
i. **Temperature:** Performance improves performance up to the optimum, then declines.

ii. **Pressure:** Performance increase because enhances reactant density and membrane hydration.

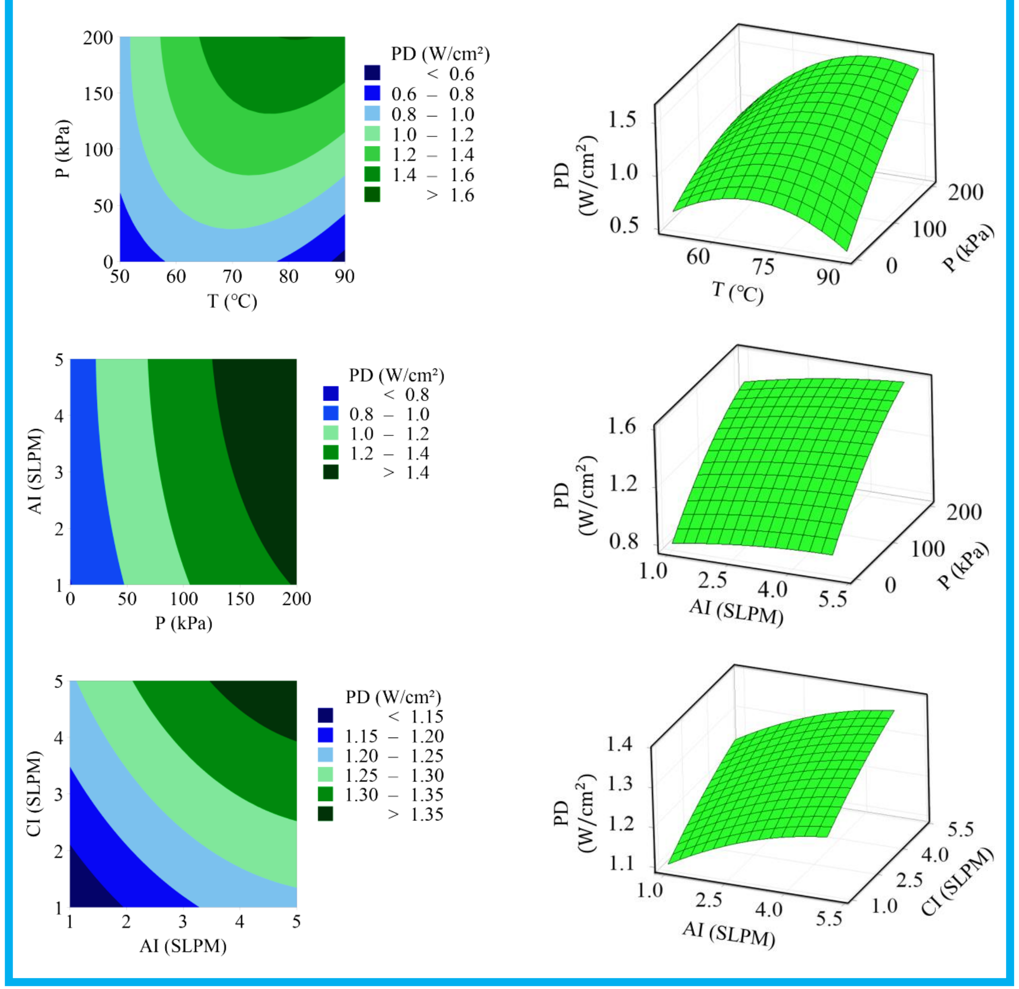
iii. **Anode Inlet Flow Rate:** Performance increase because more hydrogen improves reactant availability.

iv. **Cathode Inlet Flow Rate:** Minor positive impact because excess oxygen limits further improvements.

ANN model

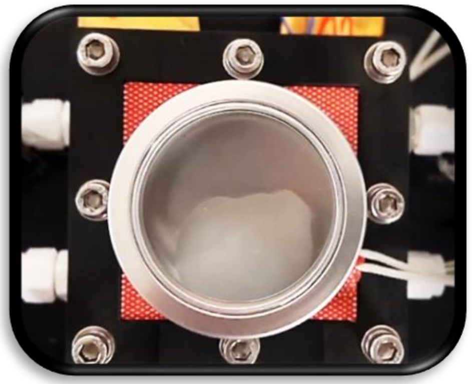


RSM model



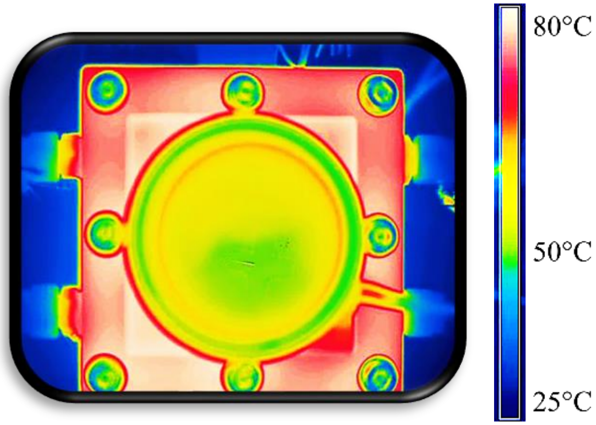
Experimental model results

Maintaining functionality during downtime using phase change material



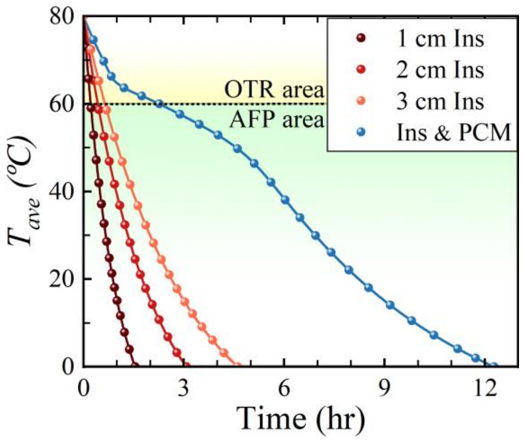
PCM melting absorbing energy

- PCM absorbs heat from PEMFC, melting non-uniformly.
- Upper PCM region melts more due to free convection currents.
- Lower PCM region remains cooler and solid.



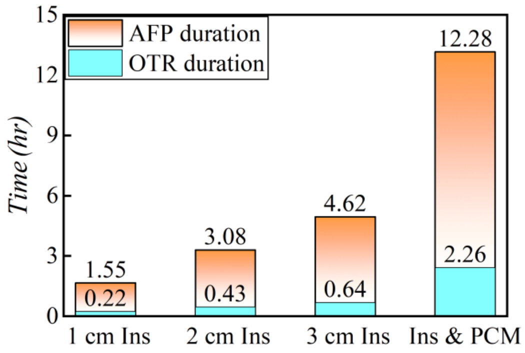
Thermal Image Analysis

- Yellow areas indicate higher temperatures and melting.
- Green areas indicate cooler temperatures and solid PCM.



Temperature Decrease During Cool Down

- Insulation and PCM slow down temperature decline.
- Plateau in temperature curve corresponds to PCM phase change duration.



Prolonged OTR and AFP

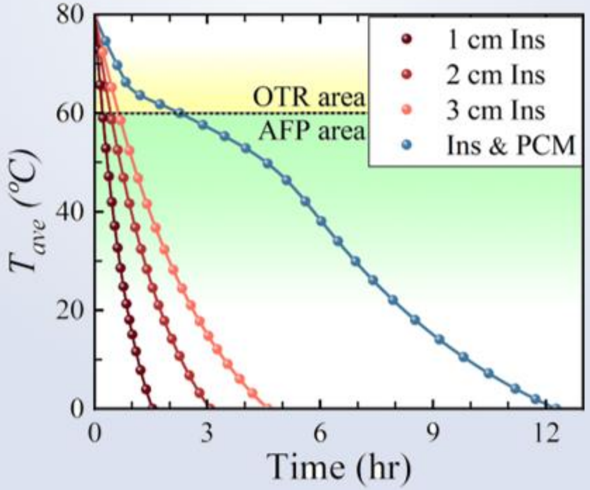
- PCM increases system's thermal mass, requiring more energy to change temperature.

Experimental model results

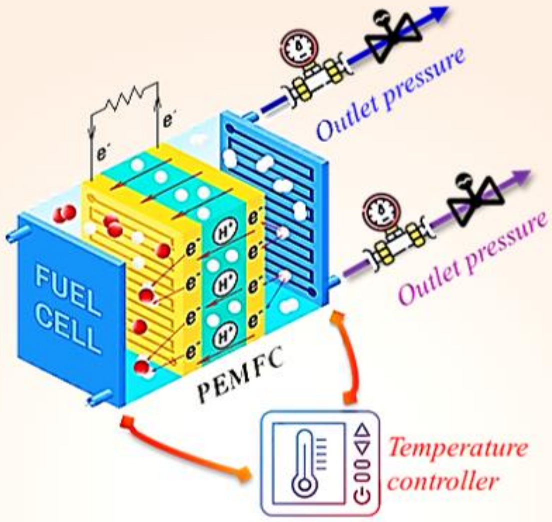
Maintaining operating temperature during downtime

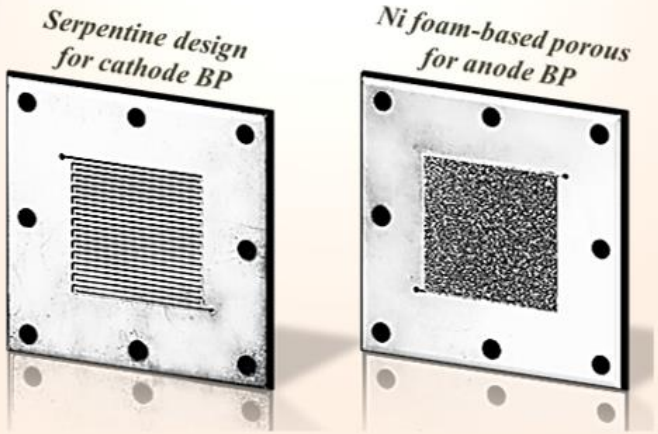
Phase change material (PCM) with 64°C melting point adopted

PCM maintained the desired range for up to 12.28 hours



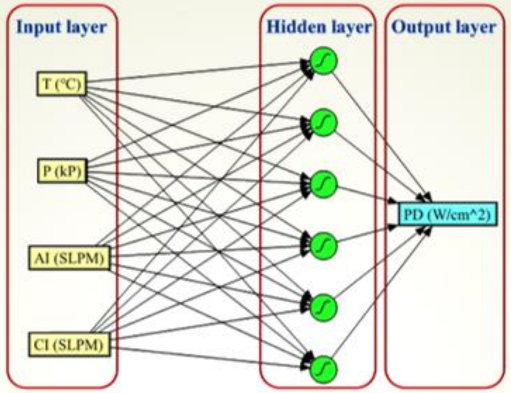
Integrated Study on the Proton Exchange Membrane Fuel Cell



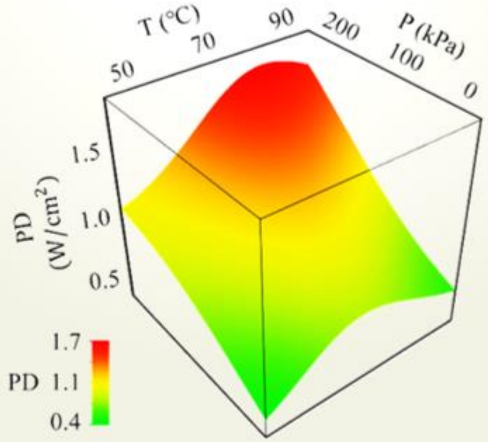


Improving PEMFC efficiency during normal operation

ANN developed for accurate PEMFC performance prediction



ANN achieved an R-squared value of 0.991



Resources

[1] Zhou Y, Chen B. Investigation of optimization and evaluation criteria for flow field in proton exchange membrane fuel cell: A critical review. Renewable and Sustainable Energy Reviews 2023;185:113584. https://doi.org/10.1016/J.RSER.2023.113584.

[2] Shahzad K, Iqbal Cheema I. Low-carbon technologies in automotive industry and decarbonizing transport. J Power Sources 2024;591:233888. https://doi.org/10.1016/J.JPOWSOUR.2023.233888.

[3] Fan R, Chang G, Xu Y, Xu J. Multi-objective optimization of graded catalyst layer to improve performance and current density uniformity of a PEMFC. Energy 2023;262:125580. https://doi.org/10.1016/J.ENERGY.2022.125580.

[4] Huang R, Peng Y, Yang J, Xu X, Deng P. Correlation analysis and prediction of PEM fuel cell voltage during start-stop operation based on real-world driving data. Energy 2022;260:124930. https://doi.org/10.1016/J.ENERGY.2022.124930.

[5] Hu D, Wang Y, Li J, Yang Q, Wang J. Investigation of optimal operating temperature for the PEMFC and its tracking control for energy saving in vehicle applications. Energy Convers Manag 2021;249:114842. https://doi.org/10.1016/J.ENCONMAN.2021.114842.

[6] Montaner Ríos G, Schirmer J, Gentner C, Kallo J. Efficient thermal management strategies for cold starts of a proton exchange membrane fuel cell system. Appl Energy 2020;279:115813. https://doi.org/10.1016/J.APENERGY.2020.115813.

[7] Huo W, Wu P, Xie B, Du Q, Liang J, Qin Z, et al. Elucidating non-uniform assembling effect in large-scale PEM fuel cell by coupling mechanics and performance models. Energy Convers Manag 2023;277:116668. https://doi.org/10.1016/J.ENCONMAN.2023.116668.

[8] Sarani I, Xie B, Bao Z, Huo W, Li X, Xu Y, et al. Analysis of phase change material thermal effects in large-scale proton-exchange membrane fuel cell based on open-source computational fluid dynamics. Appl Therm Eng 2022;216:119143. https://doi.org/10.1016/J.APPLTHERMALENG.2022.119143.

[9] Sarani I, Payan S, Payan A, Nada SA. Enhancement of energy storage capability in RT82 phase change material using strips fins and metal-oxide based nanoparticles. J Energy Storage 2020;32:102009. https://doi.org/10.1016/J.EST.2020.102009.

[10] Shen ZG, Chen S, Liu X, Chen B. A review on thermal management performance enhancement of phase change materials for vehicle lithium-ion batteries. Renewable and Sustainable Energy Reviews 2021;148:111301. https://doi.org/10.1016/J.RSER.2021.111301.

[11] Sarani I, Payan S, Nada SA, Payan A. Numerical investigation of an innovative discontinuous distribution of fins for solidification rate enhancement in PCM with and without nanoparticles. Appl Therm Eng 2020;176:115017. https://doi.org/10.1016/J.APPLTHERMALENG.2020.115017.

[12] Hosseini, S. E. (2024). Hydrogen fuel, a game changer for the world’s energy scenario. International Journal of Green Energy, 21(6), 1366-1382.

Thanks for your attention!