Efficient Analysis of Immersion Cooling of Li-Ion Batteries

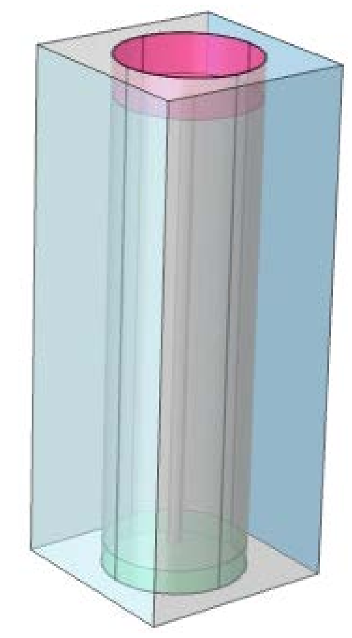
PhD student: Piyush Mani Tripathi
PI: Prof. Amy Marconnet

PURDUE ENGINEERING
engineering.purdue.edu/MTEC

- **Immersion cooling**, where the cooling fluid flows in **direct contact with the Li-ion cell**, provides **superior temperature control** compared to other battery thermal management systems (BTMSs).
- Numerical models must **fully couple** the **electrochemical** and **thermal-fluid physics** solvers for **accurate design and evaluation**.
- However, this is **computationally expensive** and may not be feasible, for large BTMSs.
- Our work focuses on developing a **computationally-efficient approach** to couple the electrochemical and thermo-fluid physics to study immersion cooling-based BTMSs.

Introduction

Fully coupled thermo-fluid-electrochemical simulations of a single 18650 cylindrical cell take ~1 to 4 days for a mass flow rate of 0.01 kg/s and 3C discharge rate. Computational time depends on whether the fluid properties depend on temperature.



Computational time for real systems with many cells becomes computationally infeasible

Modeling Framework

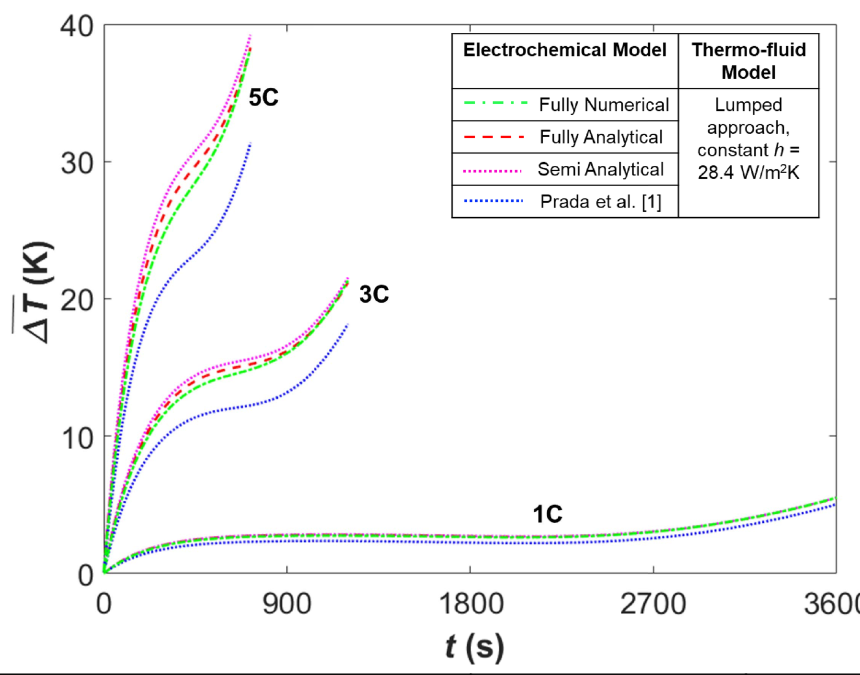
P2D Electrochemical model: 4 partial differential eqns. & 1 algebraic equation

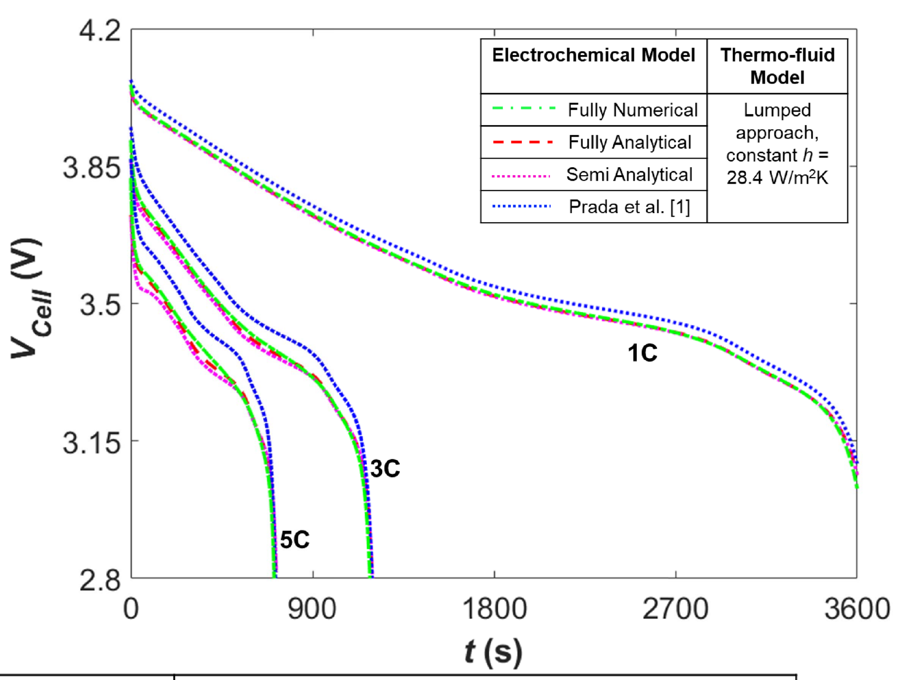
Thermo-fluid model: Lumped model using heat transfer coefficient (*h*) to account cooling behavior

Governing Equations ↓ / Solution Techniques →	Electrochemical Model Types: Fully Numerical	Semi Analytical	Fully Analytical
Charge-Electrode	*Numerical*	*Analytical*	*Analytical*
Charge-Electrolyte	*Numerical*	*Analytical*	*Analytical*
Species-Electrode	*Numerical*	*Analytical*	*Analytical*
Species-Electrolyte	*Numerical*	*Numerical*	*Analytical*

Comparison: Average temperature rise ($\overline{\Delta T}$) & Cell potential (V_{Cell})

- All models have been implemented in MATLAB.
- Both submodules (electrochemical & thermo-fluid) are solved recursively marching ahead in time.
- Fully numerical is used as reference to judge accuracy.





Fully Coupled Model ↓ / Characteristics →		Computational cost* @ 3C	Accuracy** @ 3C (Mean error, %)		Validity
Electrochemical Model	**Thermo-fluid Model**		V_{Cell}	$\overline{\Delta T}$	
Fully Numerical	Lumped approach, constant *h* = 28.4 W/m²K	*~1200 s*	*0 (Reference)*		*All discharge rates*
Fully Analytical		*~0.1 s*	*0.3*	*2.9*	*Up to 5C discharge rate with few exceptions*
Semi Analytical		*~18 s*	*0.5*	*5.5*	*All discharge rates*
Prada et al. [1]		*~141 s*	*1.6*	*16*	*All discharge rates*

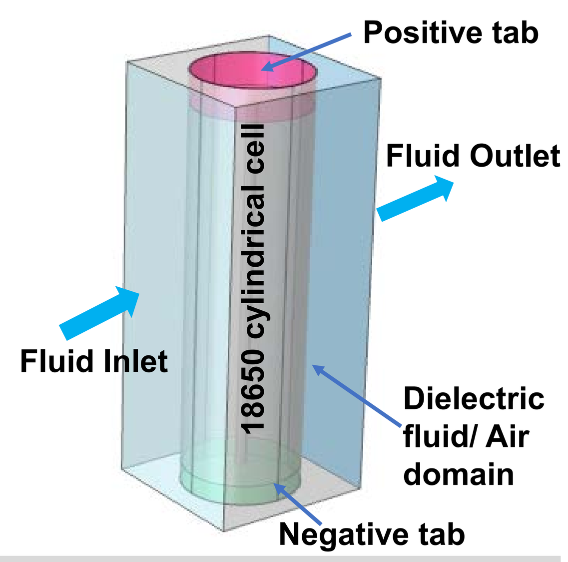
*System: Processor - Intel(R)Xeon(R)@3.30GHz & RAM-16GB. **For same set of parameters and properties.

Model Implementation for Immersion Cooling

Types of Fully-Coupled Immersion Cooling Model

- Fully Numerical electrochemical model + Detailed thermo-fluid numerical model = Numerical Model
- Fully Analytical / Semi Analytical electrochemical model + Lumped thermal model based on available heat transfer correlation = Analytical Model
- Fully Analytical / Semi Analytical electrochemical model + Lumped thermal model based on trained heat transfer correlation = Quasi–Analytical Model

Immersion Cooling Domain

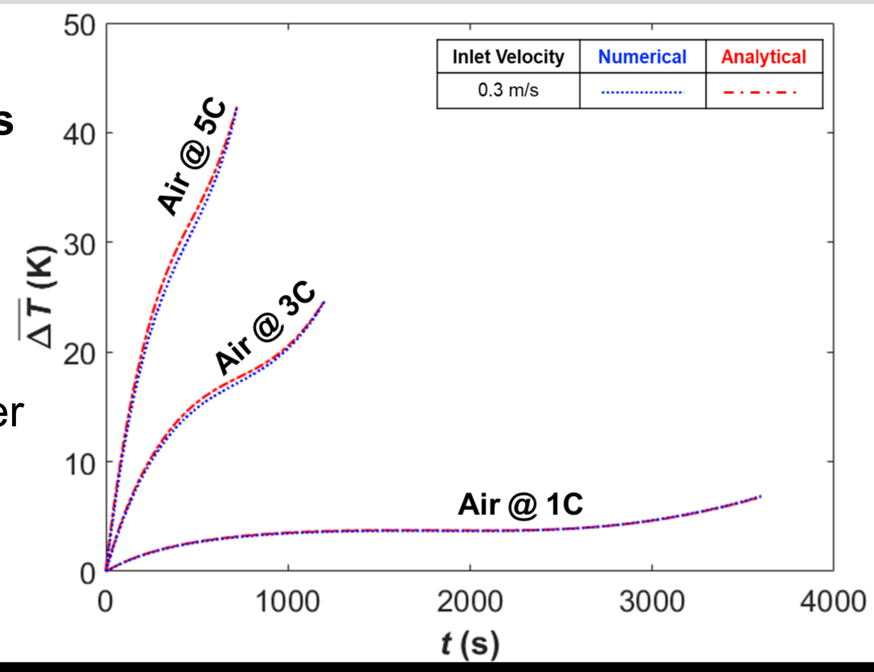


Analytical Model of Immersion Cooling Model: Air

- Usually **heat transfer correlations** have been developed to predict heat transfer as **function of dimensionless numbers** like Reynolds number (*Re*), Prandtl number (*Pr*).
- For the **cylinder in the duct cross flow**, heat transfer correlation from literature [2]:

$$h = (\lambda/D)0.655Re^{0.471}Pr^{(1/3)}\left(1+\sqrt{D/W}\right)$$

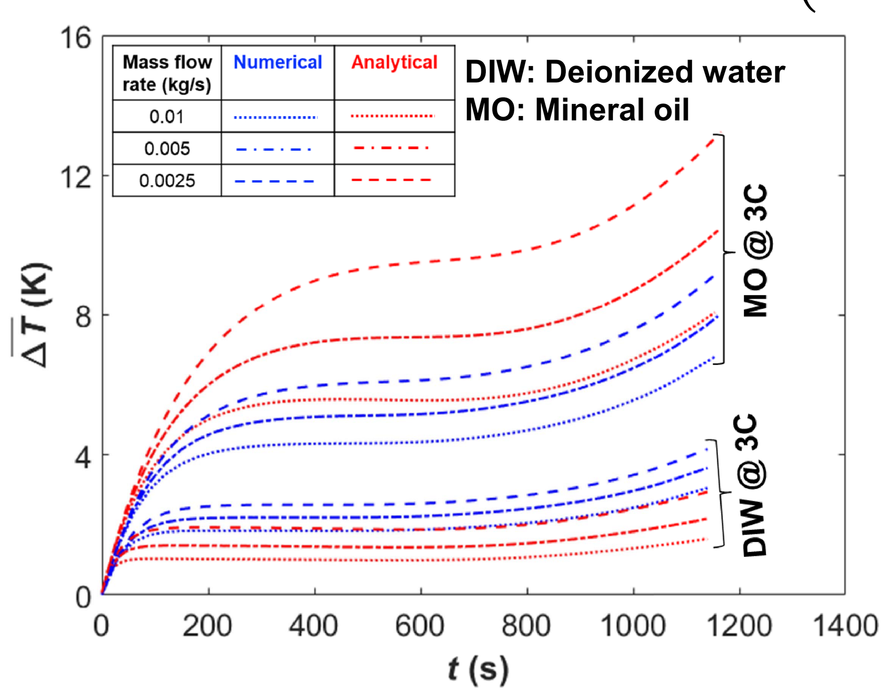
- Above correlation **accounts geometry affects** using diameter (*D*) and width of the duct (*W*).
- For this configuration, analytical model predicts $\overline{\Delta T}$ in **agreement with numerical model**.



Results and Discussion

Analytical Model of Immersion Cooling Model: Dielectric Fluid

$$h = (\lambda/D)0.655Re^{0.471}Pr^{(1/3)}\left(1+\sqrt{D/W}\right)$$



Pro: Predicts right trend and order of magnitude of $\overline{\Delta T}$.

Con: Exact magnitude of $\overline{\Delta T}$ differs significantly except for air (for this configuration).

Primary reasons that analytical model does not predict exact magnitudes of $\overline{\Delta T}$:

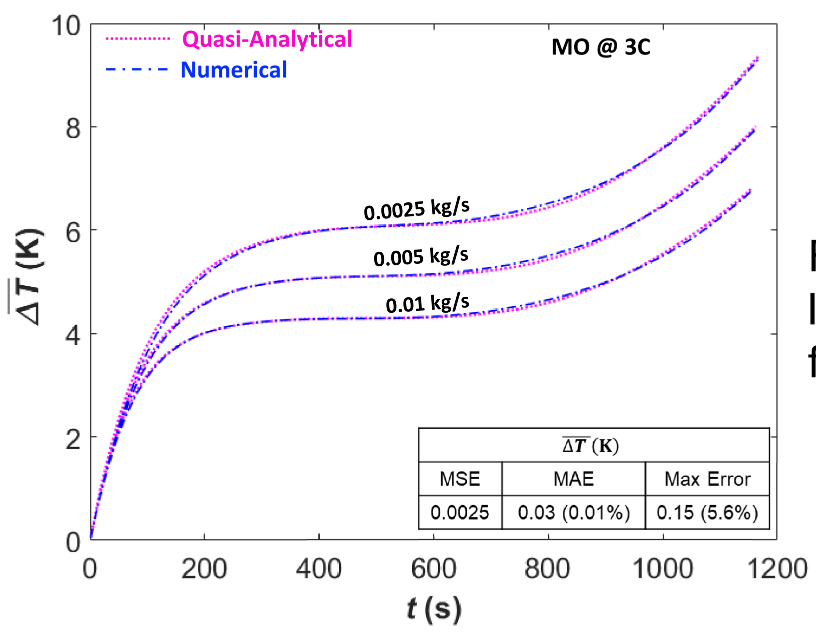
1. Heat transfer correlations are usually developed for **steady state condition**.
2. Geometry used for correlations are **different** from the **actual configurations**.
3. Valid for **standard boundary condition**: Constant temperature or heat flux.

Quasi-Analytical Immersion Cooling Model: Dielectric Fluid

Trained heat transfer correlations,

$$h = (\lambda/D)aRe^{b}Pr^{c}\left(1+\sqrt{D/W}\right)\left(1+e^{-Fo/d}\right),\ h = f(a,b,c,d)$$

Above proposed heat transfer correlations can be trained with either **numerical** or **experimental** data sets.

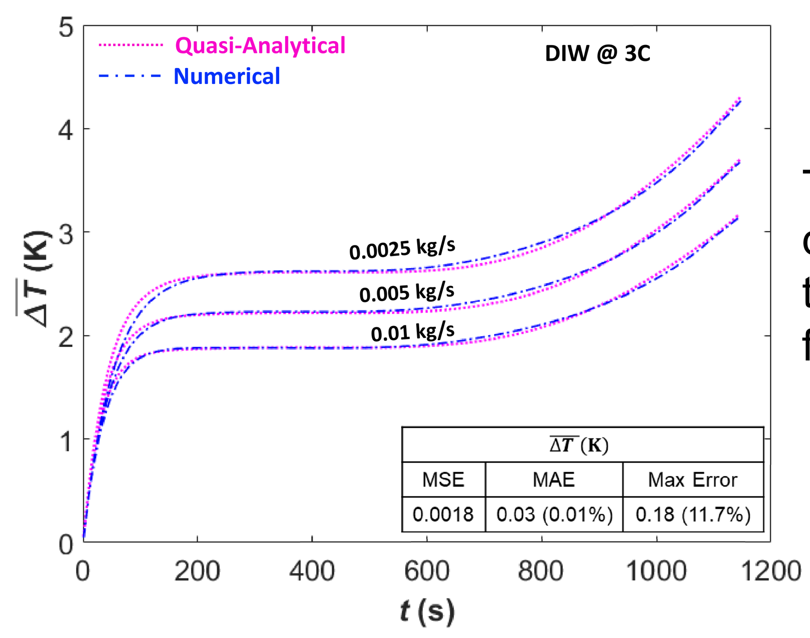


MSE: Mean squared error
MEA: Mean absolute error

Fitted values of power law coefficients for two fluids:

MO
a = 0.55 c = 1/3
b = 0.26 d = 5.62

DIW
a = 0.51 c = 1/3
b = 0.28 d = 11.10



There is a significant difference in the transient term '*d*' between the two fluids.

- Predictions are very **accurate** and **computationally efficient**.
- Requires only **two mass flow rates** for each fluid **at a given discharge rate** to train *h* correlations.

Conclusion

- **Proposed models** including the numerical data-driven learning provide an **efficient trade-off** between **computation cost** and **accuracy**.
- The developed model can be easily upscaled for large BTMS, therefore will **accelerate the design and analysis** of immersion cooling systems.
- Approach will be handy in **real-time applications** such as **dynamic immersion cooling** where parameters are tuned based on operating conditions.

References

1. E. Prada et. al., "Simplified Electrochemical and Thermal Model of LiFePO 4 -Graphite Li-Ion Batteries for Fast Charge Applications ," Journal of The Electrochemical Society, vol. 159, no. 9, pp. A1508–A1519, 2012
2. R. J. Pederson and E. M. Sparrow, "Heat Transfer From a Cylinder in Crossflow Situated in a Turbulent Pipe Flow," Journal of Heat Transfer, vol. 99, pp. 425–432, 8 1977

Acknowledgement

This material is based upon work supported by the National Science Foundation under Grant No. 2143043. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.