P / O / E / T / S

CENTER FOR POWER OPTIMIZATION OF ELECTRO-THERMAL SYSTEMS

Virtual Testbed for Fast Charging Battery Systems

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Outline

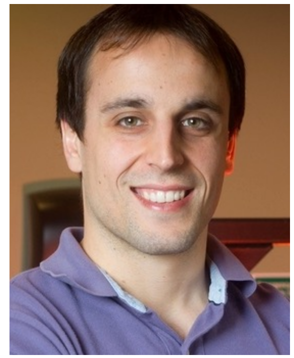
1. Modelling Environment
2. Virtual Testbed System Blocks
3. System Level Battery Thermal Management Model
4. Battery Fast Charging with Active Cooling
5. Battery Preconditioning
6. Battery Discharge during Drive Cycle
7. Results Summary:
   - i) Battery Charging,
   - ii) Preconditioning
   - iii) Discharging

POETS Collaborators

STANFORD nanoHeat

Goodson group

ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

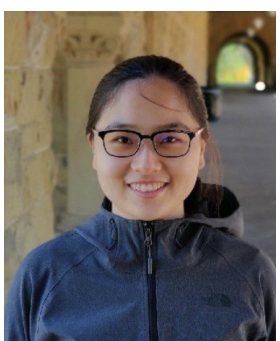


Miljkovic group

UNIVERSITY OF MINNESOTA
Driven to Discover

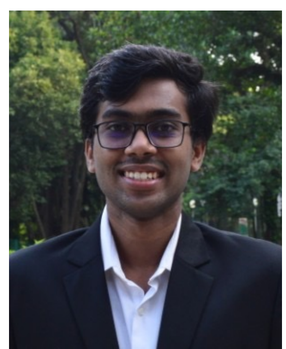
Alleyne group

Katherine Jiang

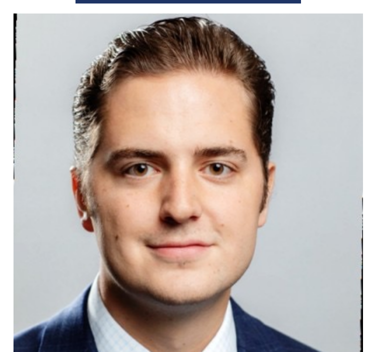


Yashraj Gurumukhi

Sagar Singh



BRUNSWICK



IAB advisor: Brennan Kelly

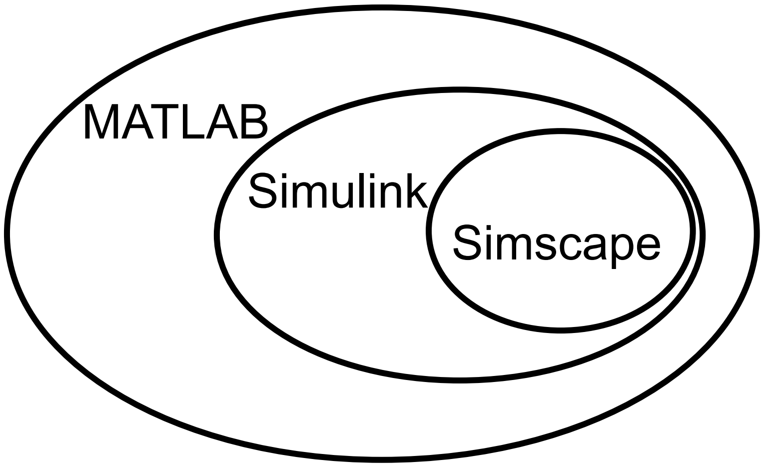
Exec Summary and Impact

Problem Statement

- Develop a system level analysis tool with reconfigurable components
- Application of the framework for evaluation of fast charging and battery thermal management strategies

Relevance to Industry

- Modelling framework provides a Virtual Testbed for simulation and analysis of EV thermal management system as well as impact of POETS and non-POETS developed technologies
- Framework can be extended to other electro-thermal applications (aircraft/naval)



MATLAB:

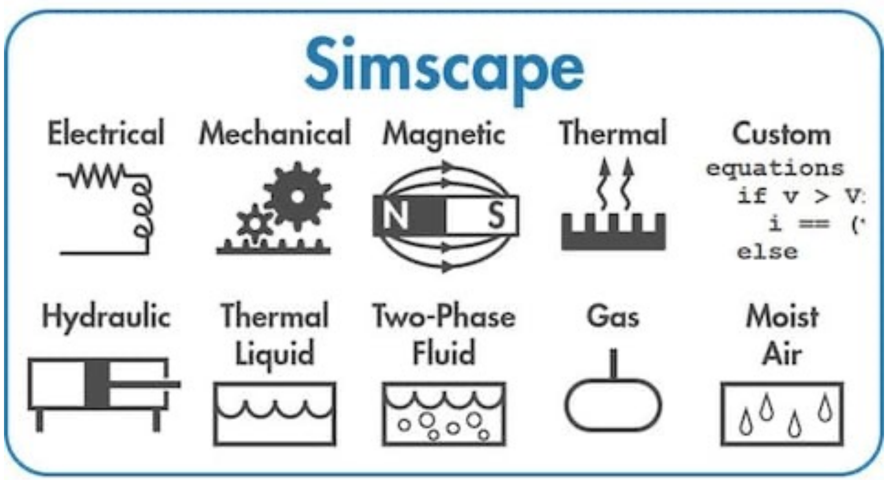
An environment built with matrix and arrays expressed mathematically

Simulink:

Environment inside MATLAB built for system design and simulation

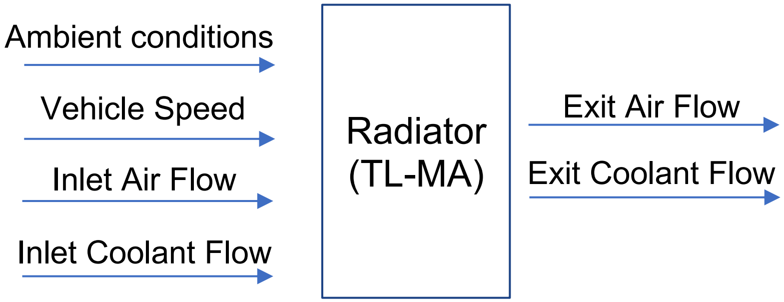
Simscape:

Library inside Simulink with built-in physical components in various domains

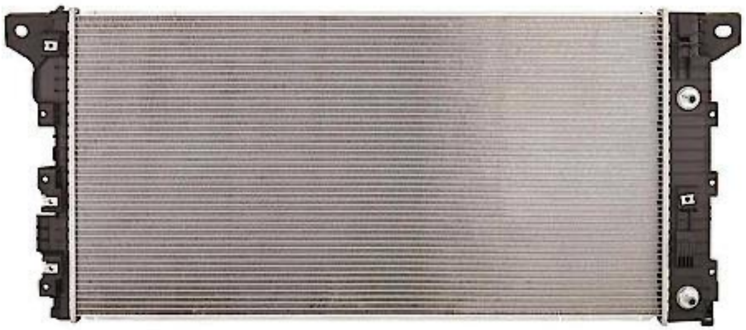


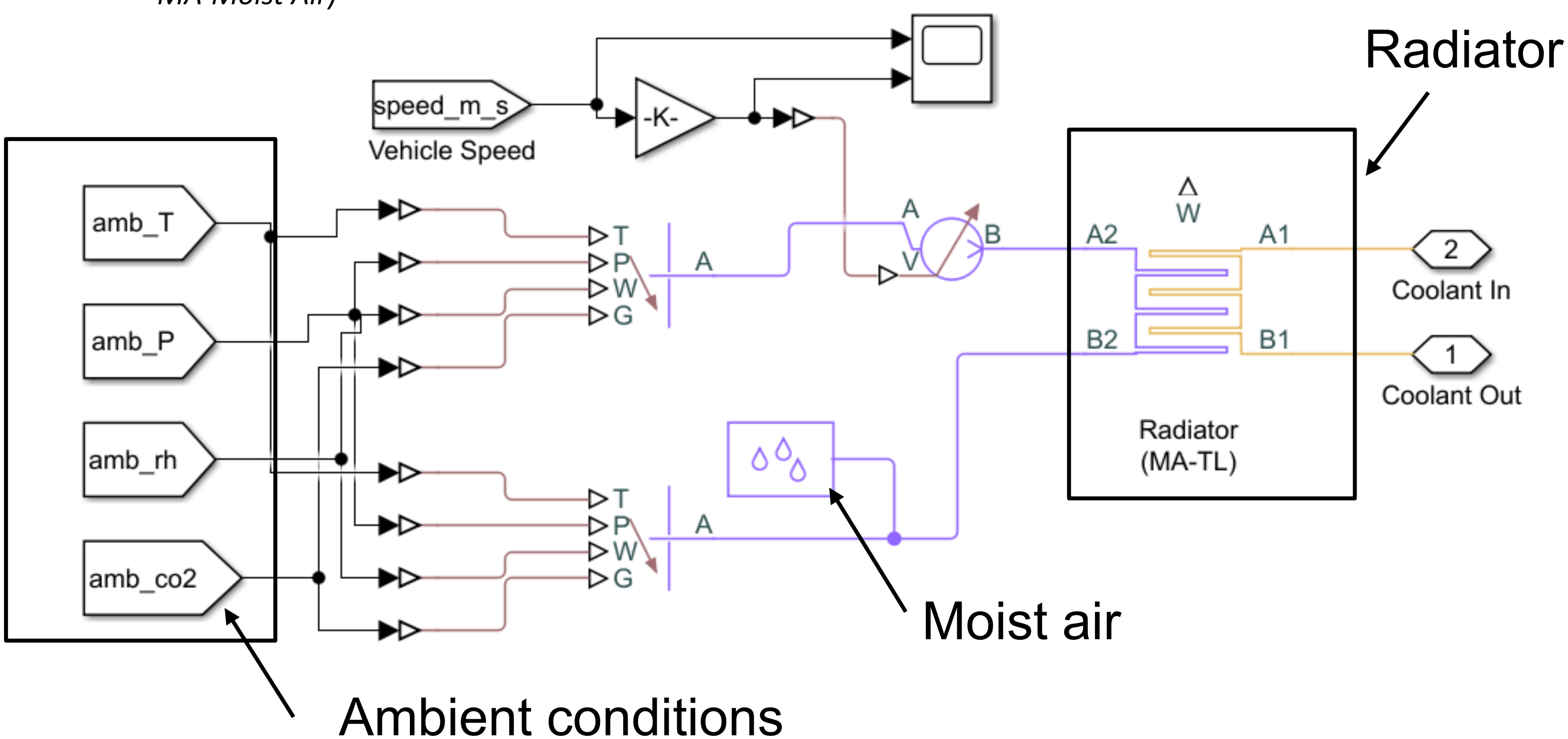
Transient Modelling

System Blocks – Example: Radiator



(TL-Thermal Liquid, MA-Moist Air)





The Back End - Governing Equations

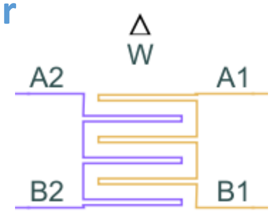
Effectiveness-NTU Heat Transfer

$$Q = \epsilon C_{\mathrm{Min}}(T_{\mathrm{In,TL}} - T_{\mathrm{In,MA}})$$

$$NTU = \frac{1}{C_{\mathrm{Min}} R}$$

$$R = \frac{1}{U_{\mathrm{TL}} A_{\mathrm{Th,TL}}} + \frac{F_{\mathrm{TL}}}{A_{\mathrm{Th,TL}}} + R_{\mathrm{W}} + \frac{F_{\mathrm{MA}}}{A_{\mathrm{Th,MA}}} + \frac{1}{U_{\mathrm{MA}} A_{\mathrm{Th,MA}}}$$

$$\epsilon = \frac{1 - \exp[-NTU(1 + C_{\mathrm{R}})]}{1 + C_{\mathrm{R}}}$$ *(Parallel flow)*



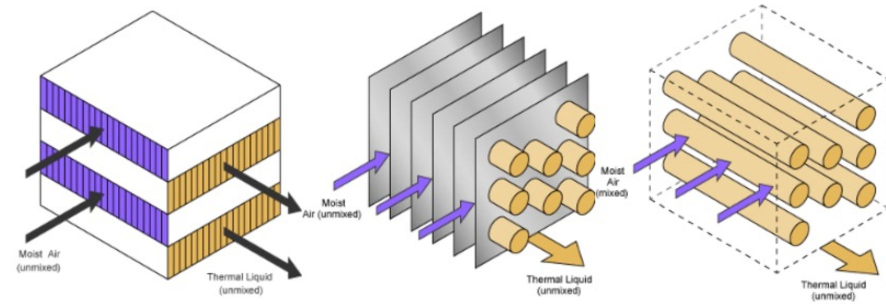


Fig: Different cross flow configurations

Heat Transfer Coefficients

$$U = \frac{\mathrm{Nu}k}{D_{\mathrm{H}}} \qquad \mathrm{Nu} = \frac{\frac{f_D}{8}(\mathrm{Re} - 1000)\mathrm{Pr}}{1 + 12.7\sqrt{\frac{f}{8}}(\mathrm{Pr}^{2/3} - 1)}$$

(Turbulent flow inside tube)

$$\mathrm{Nu} = \begin{cases} 0.404 Lq^{1/3}\left(\frac{\mathrm{Re}+1}{\mathrm{Re}+1000}\right)^{0.1}, & Inline \\ 0.404 Lq^{1/3}, & Staggered \end{cases}$$

(Flow across tube bank)

Conservation Equations

$$\frac{dM_{\mathrm{TL}}}{dt} = \dot{m}_{\mathrm{A1}} + \dot{m}_{\mathrm{B1}} \qquad \frac{dM_{\mathrm{MA}}}{dt} = \dot{m}_{\mathrm{A2}} + \dot{m}_{\mathrm{B2}} - \dot{m}_{\mathrm{Cond}}$$

$$M_{TL}\frac{du_{TL}}{dt} + u_{TL}(\dot{m}_{A1} + \dot{m}_{B1}) = \phi_{\mathrm{A1}} + \phi_{\mathrm{B1}} - Q$$

$$M_{MA}\frac{du_{MA}}{dt} + u_{MA}(\dot{m}_{A2} + \dot{m}_{B2} - \dot{m}_{Cond}) = \phi_{\mathrm{A2}} + \phi_{\mathrm{B2}} + Q - \phi_{\mathrm{Cond}}$$

Pressure Loss

$$p_{\mathrm{A1}} - p_{\mathrm{I1}} = \frac{f_{\mathrm{D,A}}\dot{m}_{\mathrm{A1}}|\dot{m}_{\mathrm{A1}}|}{2\rho D_{\mathrm{H}} A_{\mathrm{CS}}^2}\left(\frac{L + L_{\mathrm{Add}}}{2}\right)$$ *(Flow inside tube)*

$$p_{\mathrm{A2}} - p_{\mathrm{I2}} = \frac{1}{2}\frac{\mu^2 N_{\mathrm{R}}}{\rho D^2}\mathrm{Hg}(\mathrm{Re})$$ *(Flow across tube bank)*

And so on for condensation, empirical formulation…

System Blocks Examples

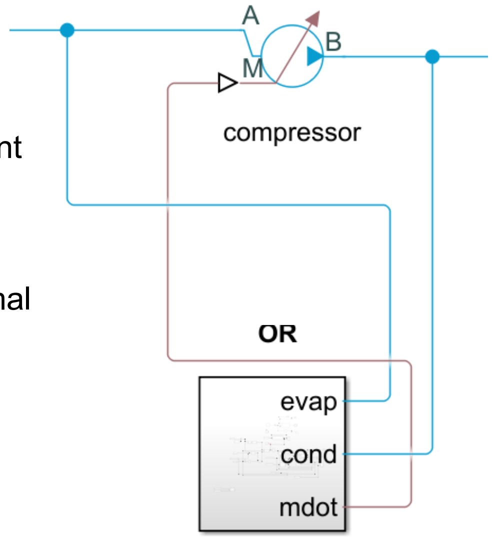
Compressor

Crucial component for refrigerant system

PID controlled refrigerant flow - based on cabin or battery thermal requirements

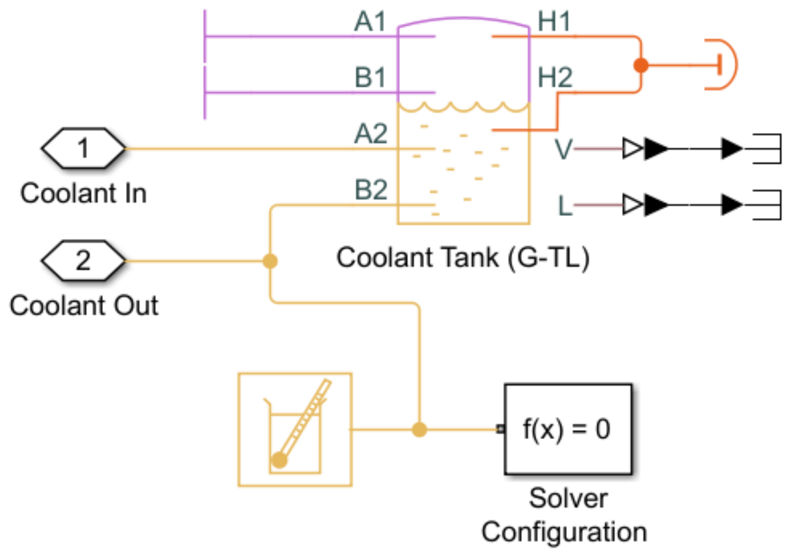
Other constraints:

- $P_{cond,max}$ ~ 2.5 MPa/360PSi
- $P_{evap,min}$ ~ 0.1 MPa/15PSi

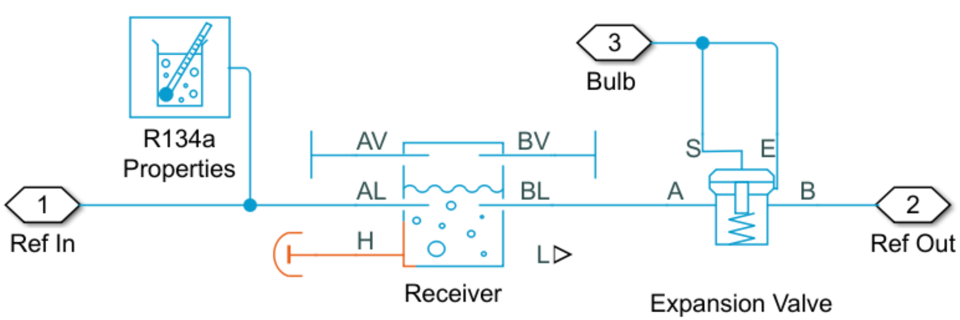


Refrigerant Mass Flow Rate Controls

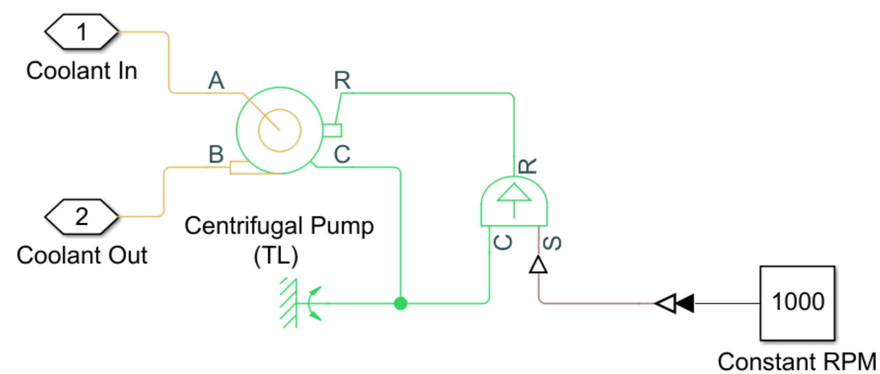
Coolant Tank



Expansion Valve and Refrigerant



Centrifugal Pump



Cell Model and Charging Protocol

Cell Parameters and Data [1]

- Cell Capacity – 28 Ah
- Type – Li-ion NMC
-

Battery Configuration

- Configuration – **80s10p** (4 packs of 20s10p each connected in series)
- Battery Energy ~ 82.9 kWh

Charging Protocol

- Constant Current Constant Constant Voltage (CC-CV)

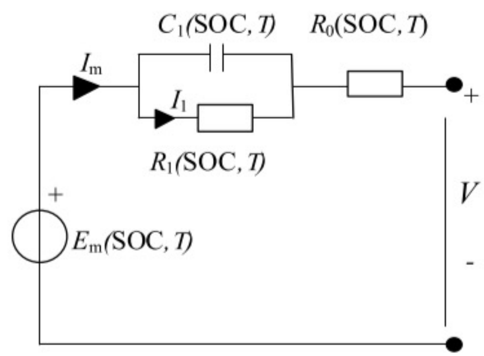


Fig 1. Simplified equivalent circuit model of an electrochemical cell [1].

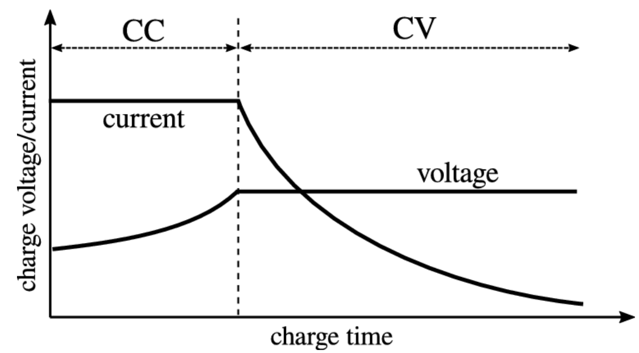
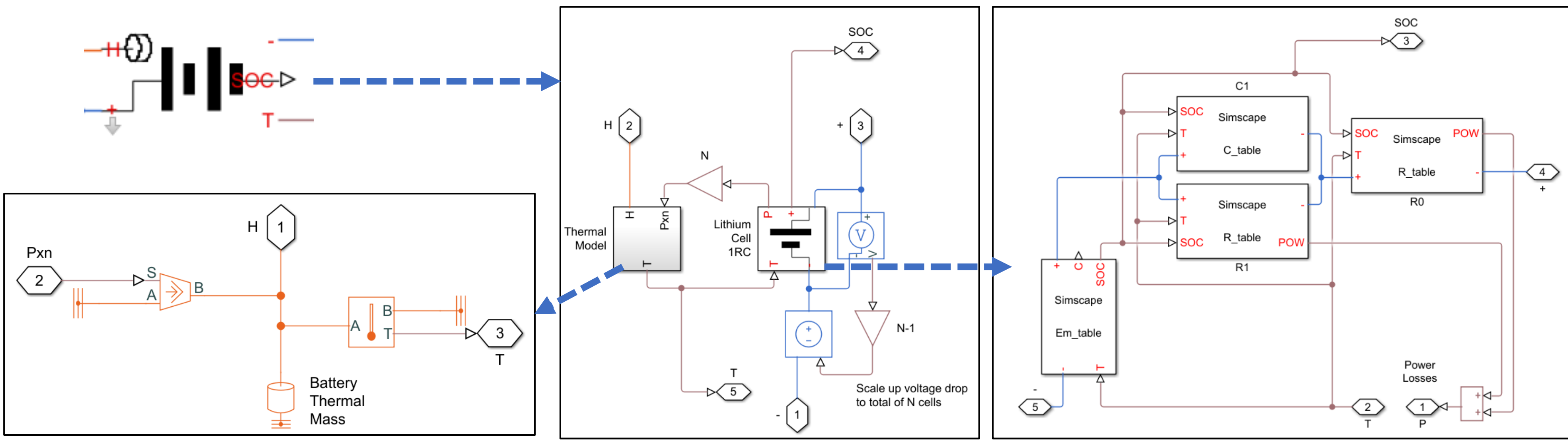


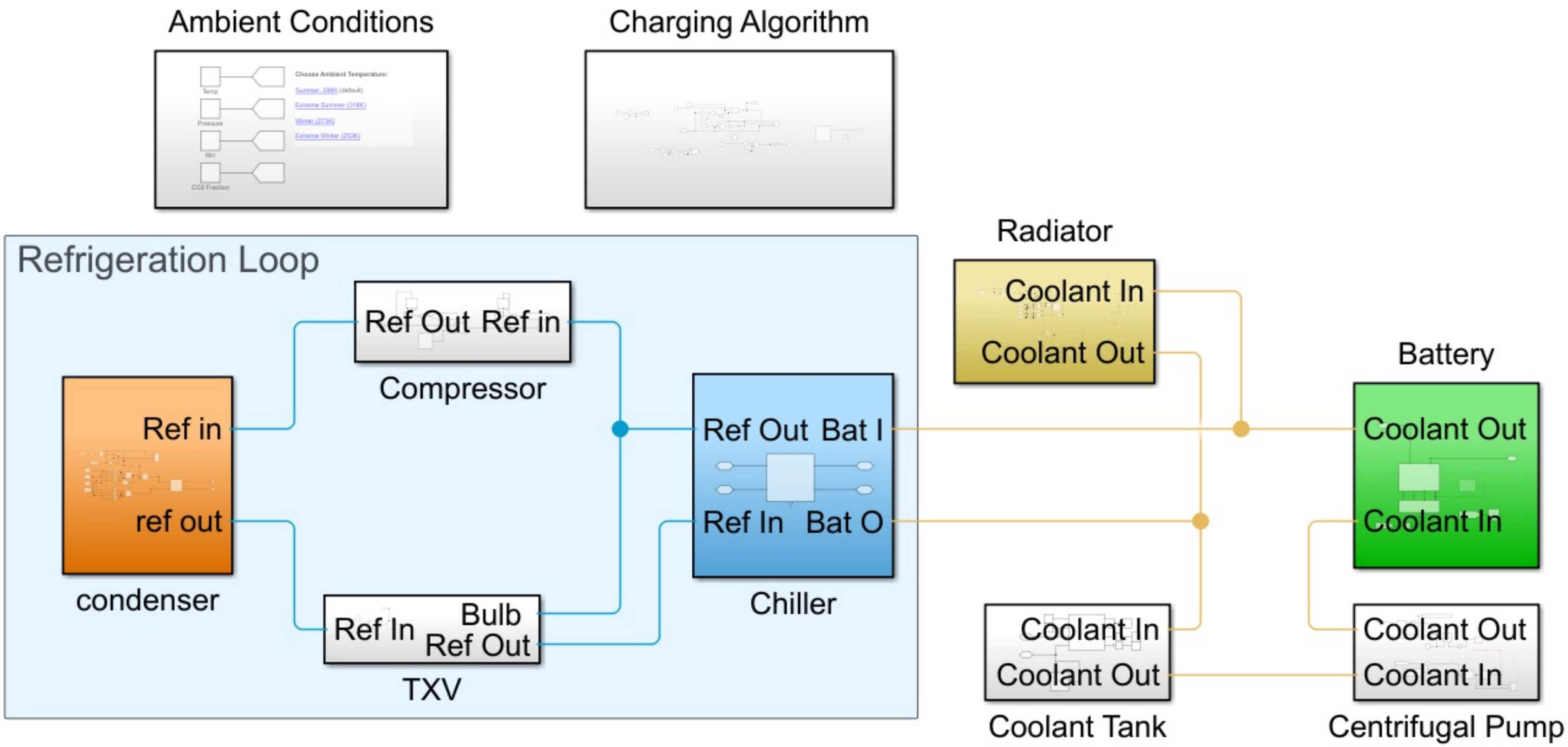
Fig 2: Charging Protocol - Constant Current Constant Voltage (**CC-CV**) [2].



[1] T. Huria, M. Ceraolo, J. Gazzarri,R. Jackey. "*High Fidelity Electrical Model with Thermal Dependence for Characterization and Simulation of High-Power Lithium Battery Cells*," IEEE International Electric Vehicle Conference, March 2012.
[2] Tomaszewska, Anna, et al. "*Lithium-ion battery fast charging: A review.*" *ETransportation* 1 (2019): 100011.

Passive cooling using radiator during low load
- Consumes pump (and fan) power

Active cooling using chiller/refrigerant system during fast charging and high load
- High energy consumption by compressor



Fast Charging with Active Cooling – Parameters

Simulated Charging Currents and C–rates

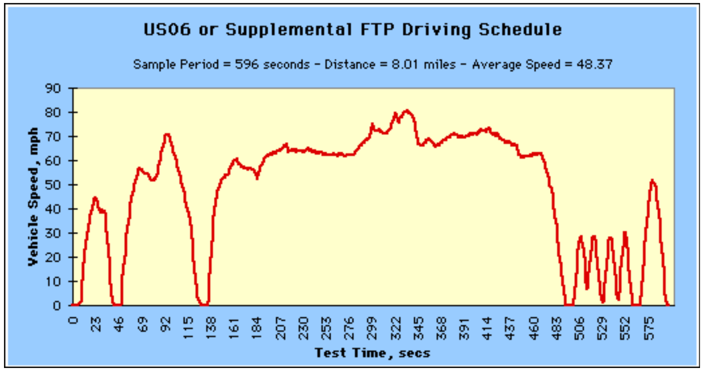
- 0.1C; 2.8*10 A = 28 A ~ 8 kW
- 0.25C; 7*10 A = 70 A ~ 21 kW
- 0.5C; 14*10 A = 140 A ~ 41 kW
- 1C; 28*10 A = 280 A ~ 83 kW
- 2C; 56*10 A = 560 A ~ 166 kW
- 3C; 84*10 A = 840 A ~ 249 kW

Parameters of Study:

- Charging Time
- Charging Energy
- Thermal Management System (Compressor + Pump) Power and Energy Consumption
- Battery Precooling Temperatures
- Max Cell Temperature During Charging
- Total Energy Consumption and Monetary Cost

Drive Cycle (for discharge)

- US 06 repeated 6 times (total 1 hour duration)



Source: *https://www.epa.gov/vehicle-and-fuel-emissions-testing/dynamometer-drive-schedules*

Fixed Simulation Parameters:

- Ambient: 30°C, relative humidity: 50%
- Battery Initial Temp = Ambient = 30°C (except for precooled battery)
- Battery desired temperature set point: 30°C
- Pump: 1000 RPM (Constant)
- Condenser fan air flow rate: 2 m^3/sec (Constant)
- Compressor refrigerant flow rate: PID Controlled

All simulations are done from 10% to 98% SOC but results are reported for 10% to 85% SOC to make it relevant for Fast Charging. After 80-85% SOC, charging rates decrease significantly.

Battery Active Cooling – 0.5C Charging

Max Cell Temp = **30.7°C**

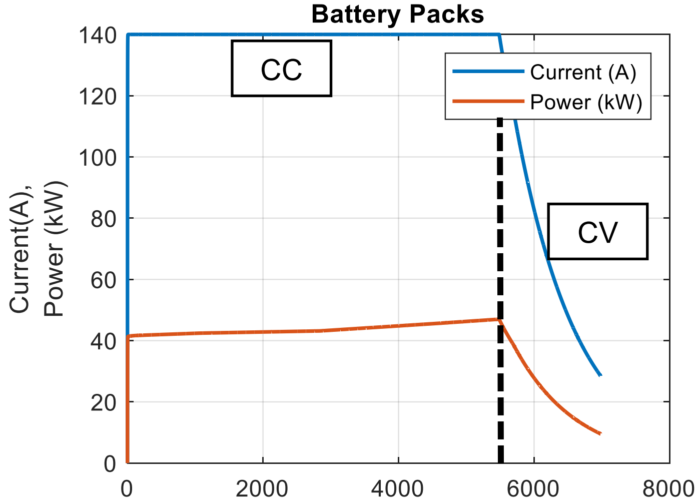
Avg. Cell Temp = **30.2°C**

Charging Time = **89 min**

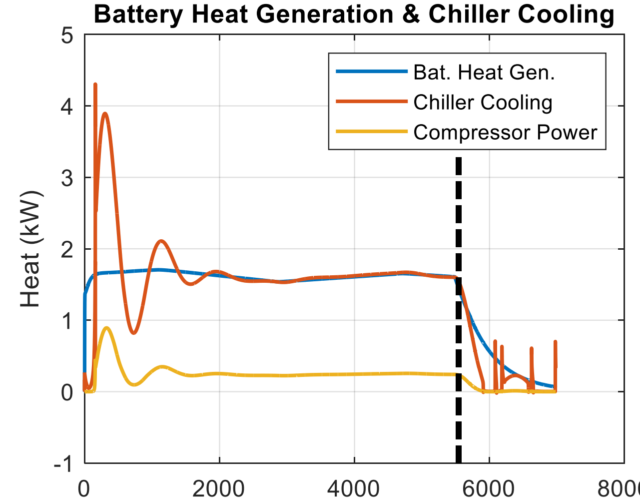
Compressor + Pump Energy **= 0.45 kWh**

Charging Energy = **64 kWh**

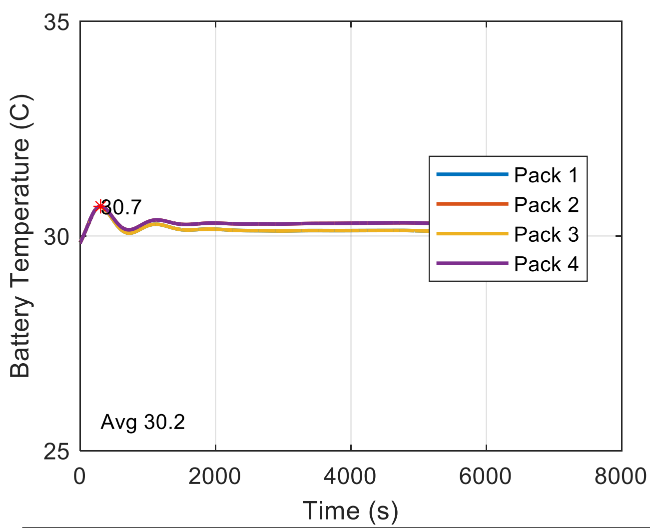
Total Energy: = **64.45 kWh**



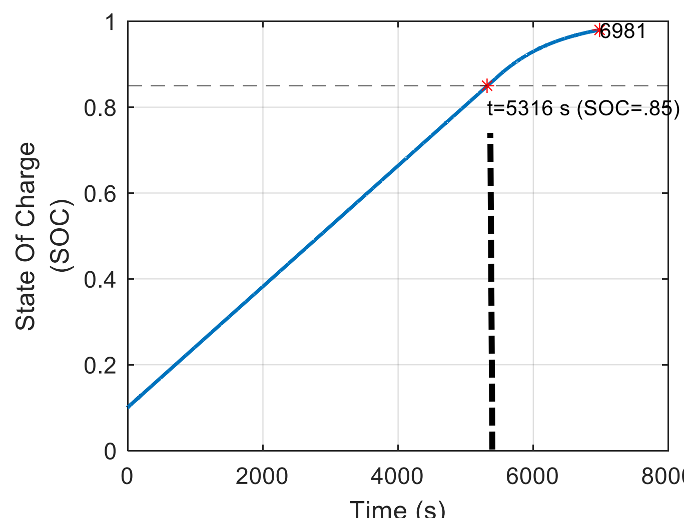
Constant Current (CV)-Constant Voltage (CV) Charging Method



Refrigerant flow rate by compressor is PID controlled



At low C-rates, cooling Power sufficient to keep the battery at desired temperature of 30C



Charging Rate decreases at the end due to switch to Constant Voltage mode

Battery Active Cooling – 2C Charging

Max Cell Temp = **59°C**

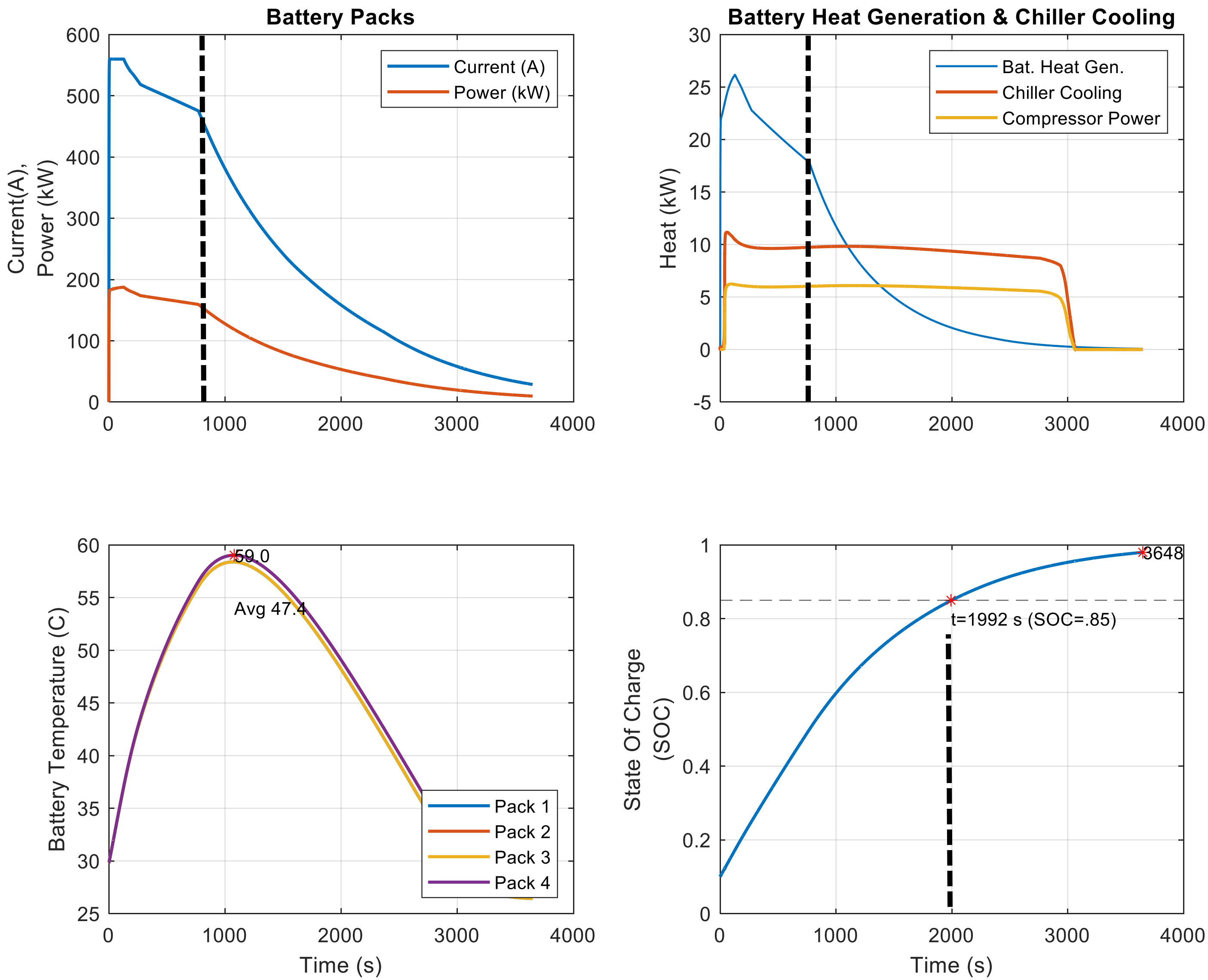
Avg. Cell Temp = **47°C**

Charging Time = **33 min**

Compressor + Pump Energy = **3.3 kWh**

Charging Energy **= 69 kWh**

Total Energy = **72.3 kWh**



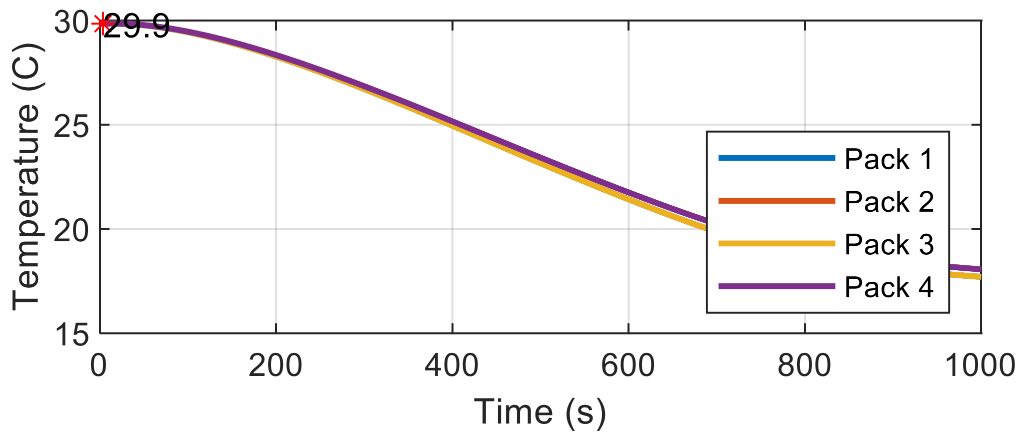
At high C-rates, cooling falls short leading to high battery max temperature during charging

Battery Preconditioning

Summer
Precooling the battery from 30°C to 20°C prior to charging

Precooling Energy (Comp. + Pump) = **1 kWh**

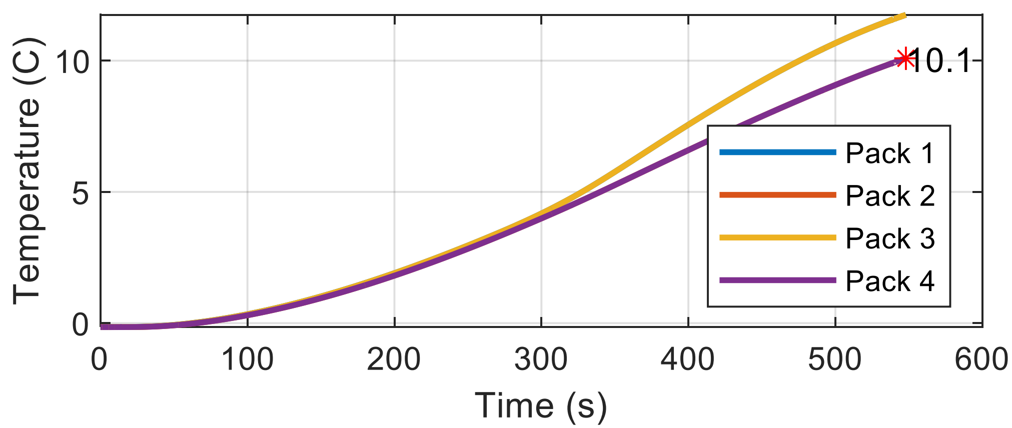
Time for Precooling = **714 s**



Winter
Preheating the battery from 0°C to 10°C prior to charging

Preheating Energy (Comp. + Pump) = **1.04 kWh**

Time for Preheating = **548 s**

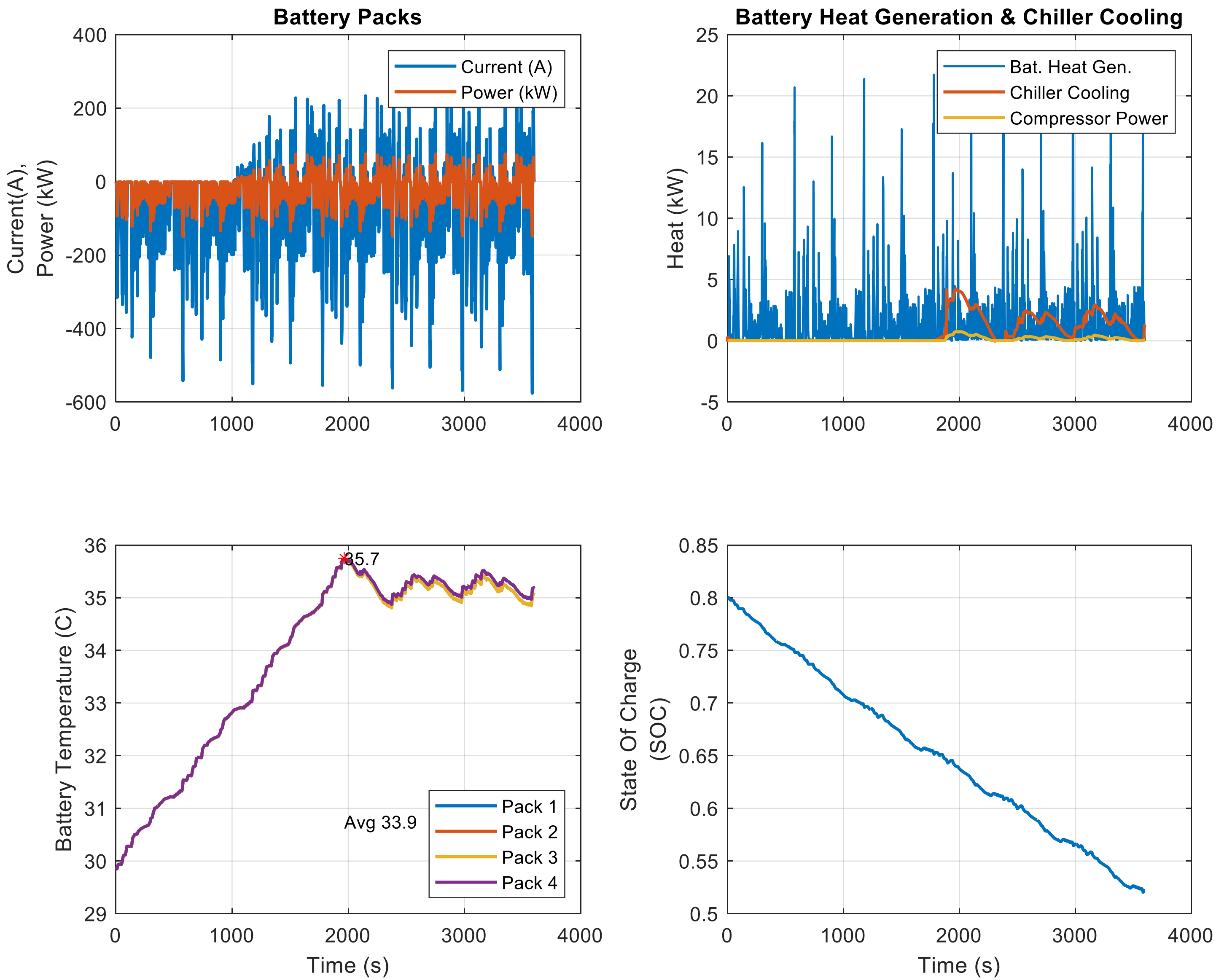


Battery Discharge (US 06 Drive Cycle)

Desired battery set point temp = **35°C**

Avg Cell Temp = **34°C**

Compressor + Pump Energy = **0.15 kWh**



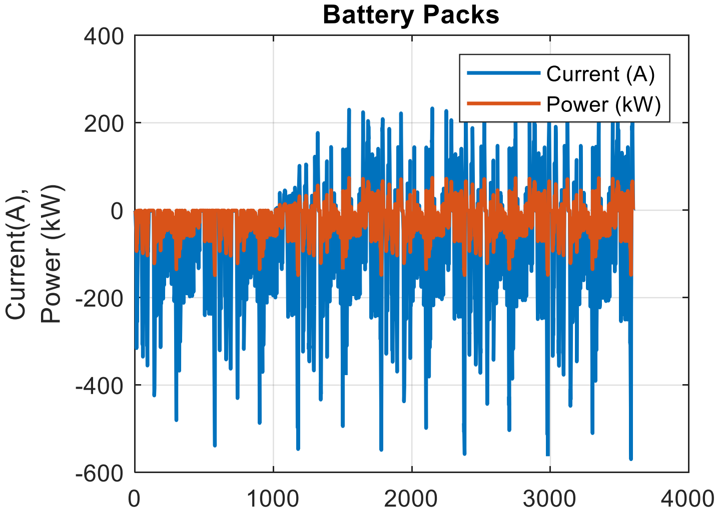
Battery Discharge (US 06 Drive Cycle)

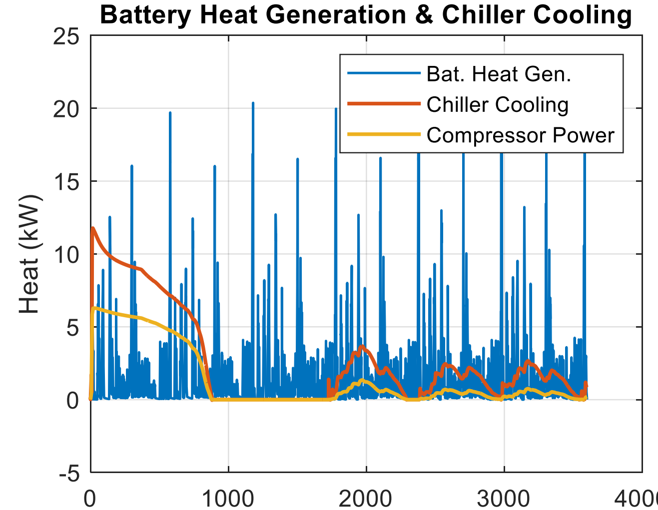
Desired battery set point temp = **20°C**

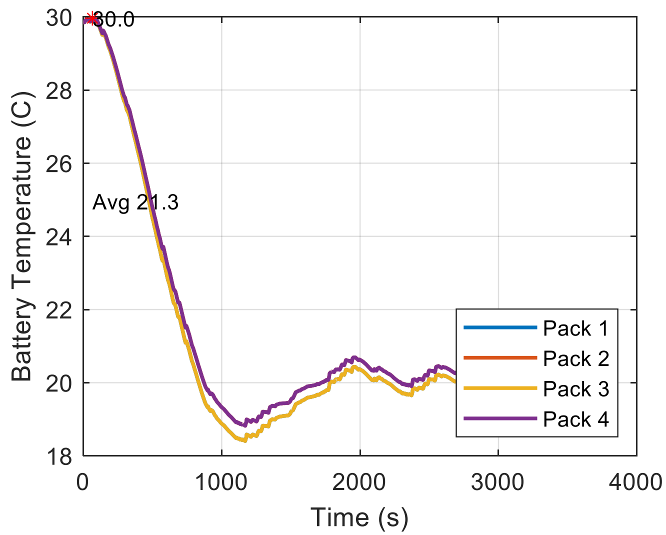
Avg Cell Temp = **21.3°C**

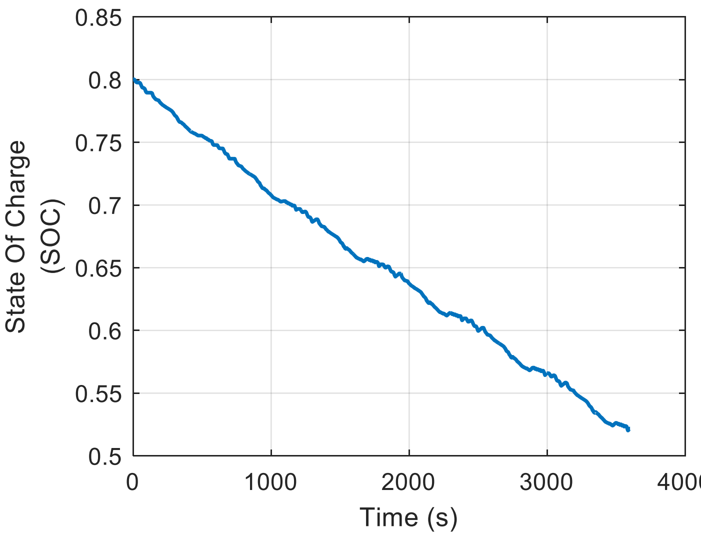
Compressor + Pump Energy = **1.42 kWh**

Higher compressor energy consumption for lower battery setpoint temperature









All values for charging from 10% to 85% SOC

Includes heat losses

Comp. + Pump Energy spent on precooling battery

C-Rate	Avg, *(Max)* Cell Temperature Reached	Comp. + Pump Energy	Charging Energy	Battery Precooling Energy	Total energy *(Comp.+ Pump + Charging + Precooling)*	Extra Energy (wrt 0.1 C)	*Annual Extra $$ (@ 0.25$/kWh , 71 cycles)	Charging Time, (Precooling time)
	(°C)	(kWh)				%, (kWh)	**$**	(min)
0.1	30.0, *(30.1)*	0.30	62.50	-	62.80	-	-	442.9
0.25	30.0, *(30.2)*	0.19	63.23	-	63.42	1.0%, *(0.62)*	**11$**	177.2
0.5	30.2, *(30.7)*	0.45	64.43	-	64.88	3.3%, *(2.08)*	**37$**	88.6
1	31.0, *(32.8)*	2.43	66.63	-	69.16	10.1%, *(6.36)*	**113$**	46.8
2	47.4, *(59.0)*	3.29	69.19	-	72.48	15.4%, *(9.68)*	**172$**	33.2
2 (precooled bat. to 25C)	44.0, *(56.3)*	3.14	69.20	0.56	72.9	16.1%, *(10.10)*	**179$**	33.3 *(7.1)*
2 (precooled bat. to 20C)	39.5, *(53.5)*	3.00	69.20	0.99	73.19	16.5%, *(10.39)*	**184$**	33.3 *(11.9)*

Very high Max Cell Temp. at 2C – Cooling power not enough

Max Cell Temperature lowers with precooled battery

Charging Energy increases with increasing C-rates due to higher heat losses

Precooling requires initial energy but leads to slightly lesser comp. power during operation

Charging time decreases with higher C-Rates

Battery Initial Temp = Ambient = 30°C
(Except for Precooled Battery)

*Avg miles driven per year by an American: 12724 [3]
Avg EV Energy consumption for 1 mile: **0.346 kWh** [4]
Avg kWh consumption per year: 12724*0.346 = 4402.5 kWh
Avg Charge Cycles: 4402.5 / ((.85-.1)*82.9)) ~ **71 cycles**

[3] Average Miles Driven Per Year: Why It Is Important - Kelley Blue Book (kbb.com)
[4] Average Electric Car kWh Per Mile [Results From 231 EVs] (ecocostsavings.com)

Preheating: Winter Charging

Ambient Temp.	Preheating Temp.	Comp. + Pump Energy	Preheating Time	Annual Preheating Cost (@ 0.25$/kWh, 71 DCFC cycles)
(°C)	(°C)	(kWh)	(min)	$ (USD)
0	5	1.04	9.1	**18**
	15	1.90	15.6	**34**

Drive Cycle – US06 repeated 6 times (total time = 1 hour)

Desired Battery Setpoint	Avg. Cell Temperature	Comp. + Pump Energy	Extra Energy (wrt 35C)	*Annual Extra $$ (@ 0.25$/kWh , 265 drive cycles)
(°C)	(°C)	(kWh)	(kWh)	**$ (USD)**
35	33.9	0.15	-	**-**
30	30.2	0.26	0.11	**7**
25	25.5	0.92	0.77	**51**
20	21.3	1.42	1.27	**84**

For $84 extra in cooling energy, lifespan of battery can potentially increase by 3 to 5 years!

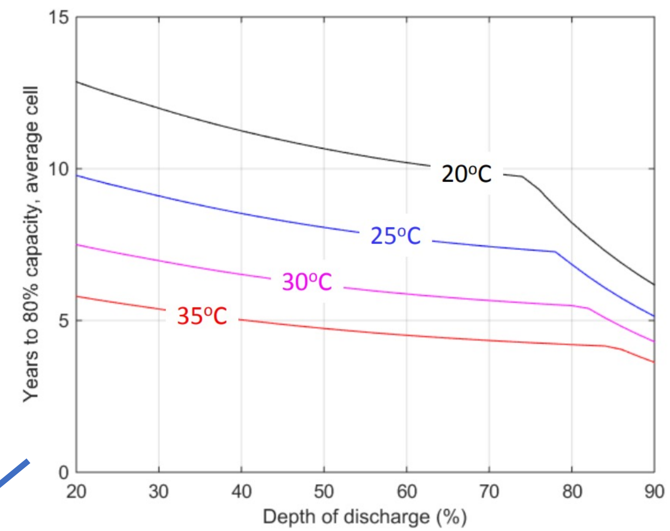


Fig: Capacity fade of a NMC/Gr. cell at different average temperatures

(K. Smith; Y. Shi; E. Wood, A. Pesaran. Advanced Automotive Battery Conference (AABC), Detroit Michigan, June, 14e17, 2016)

Plans for remaining 3 months

- Continue developing, tuning and validating thermal and electrical Virtual Testbed components.
- Develop more detailed battery models with more emphasis on temperature effects (internal gradients), cell degradation and ageing.
- Continue evaluating various battery management strategies for optimizing short term and long-term battery performance and life.

Thank You!

Questions?

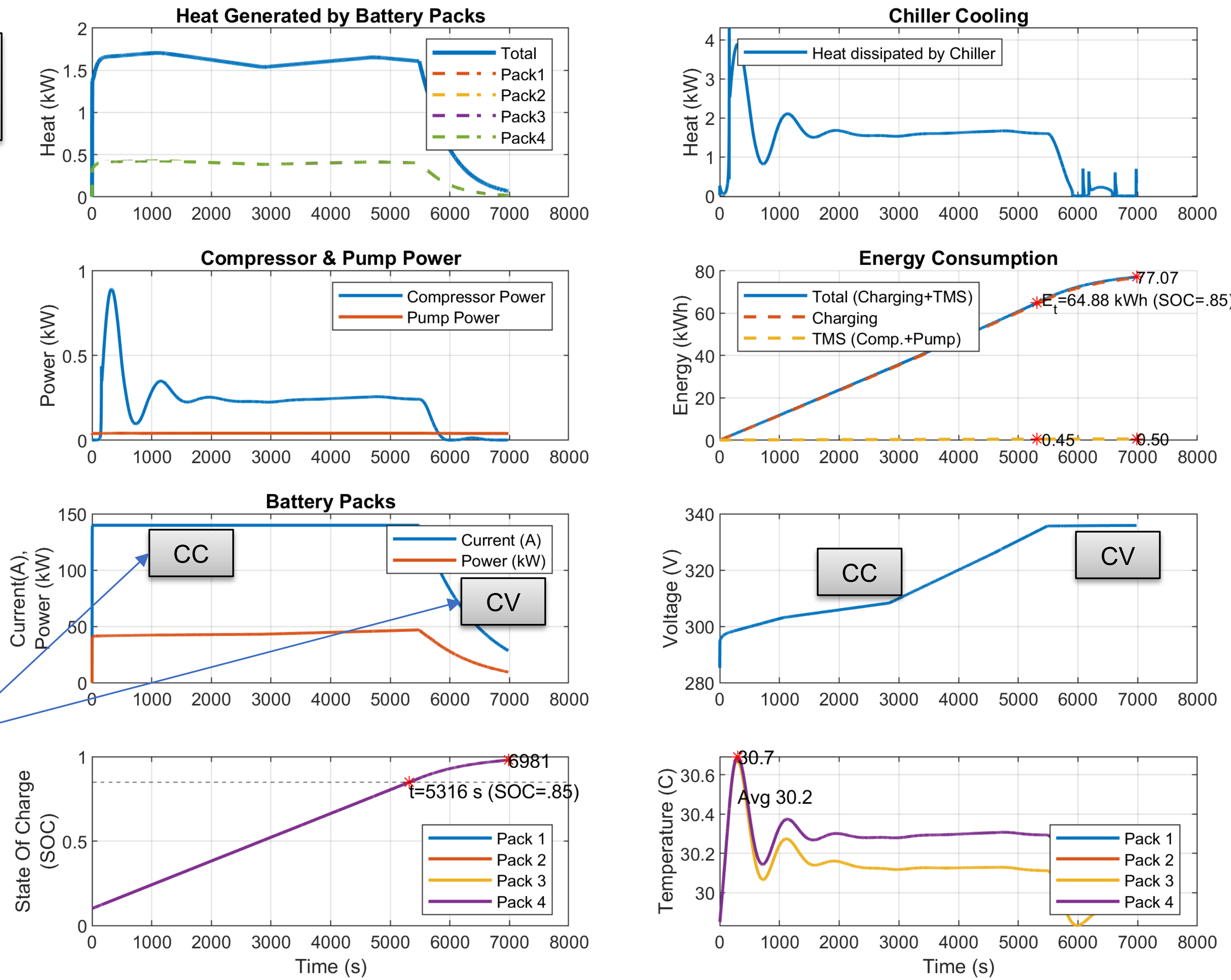
Backup Slides

Battery Active Cooling – 0.5C Charging

At low C-rates, cooling Power sufficient to keep the battery at desired temperature of 30C

Max & Avg. Cell Temp:
= 30.7°C & 30.2°C
Charging Time : 5316s
= 88.6 min
Compressor + Pump
Energy : **= 0.45 kWh**
Charging Energy:
= 64.43 kWh
Total Energy (Charging + Comp. + Pump):
= 64.88 kWh

Constant Current (CV)-Constant Voltage (CV) Charging Method

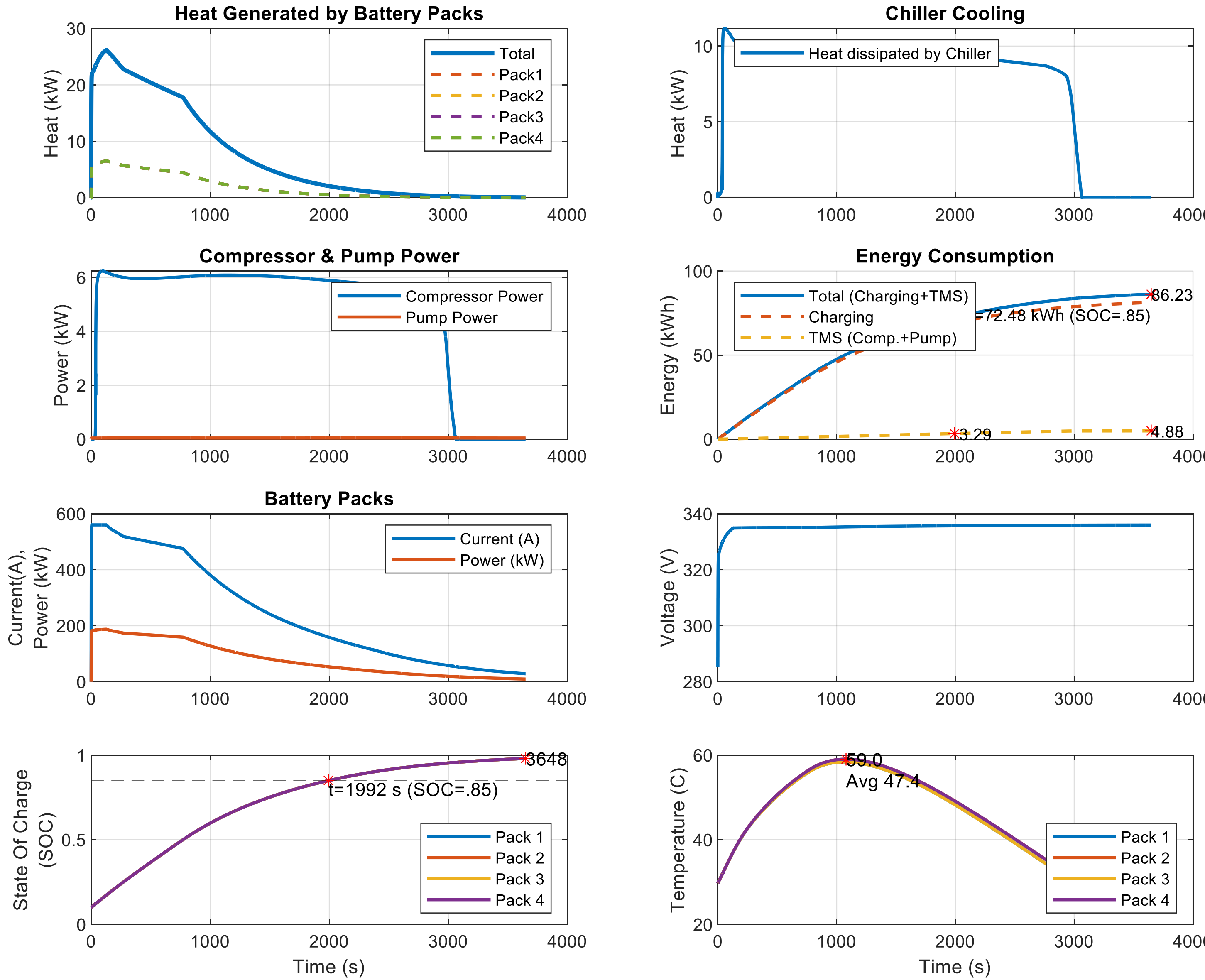


P O E T S

Battery Active Cooling – 2C Charging

At high C-rates, Cooling Power falls short leading to high battery max temperature during charging

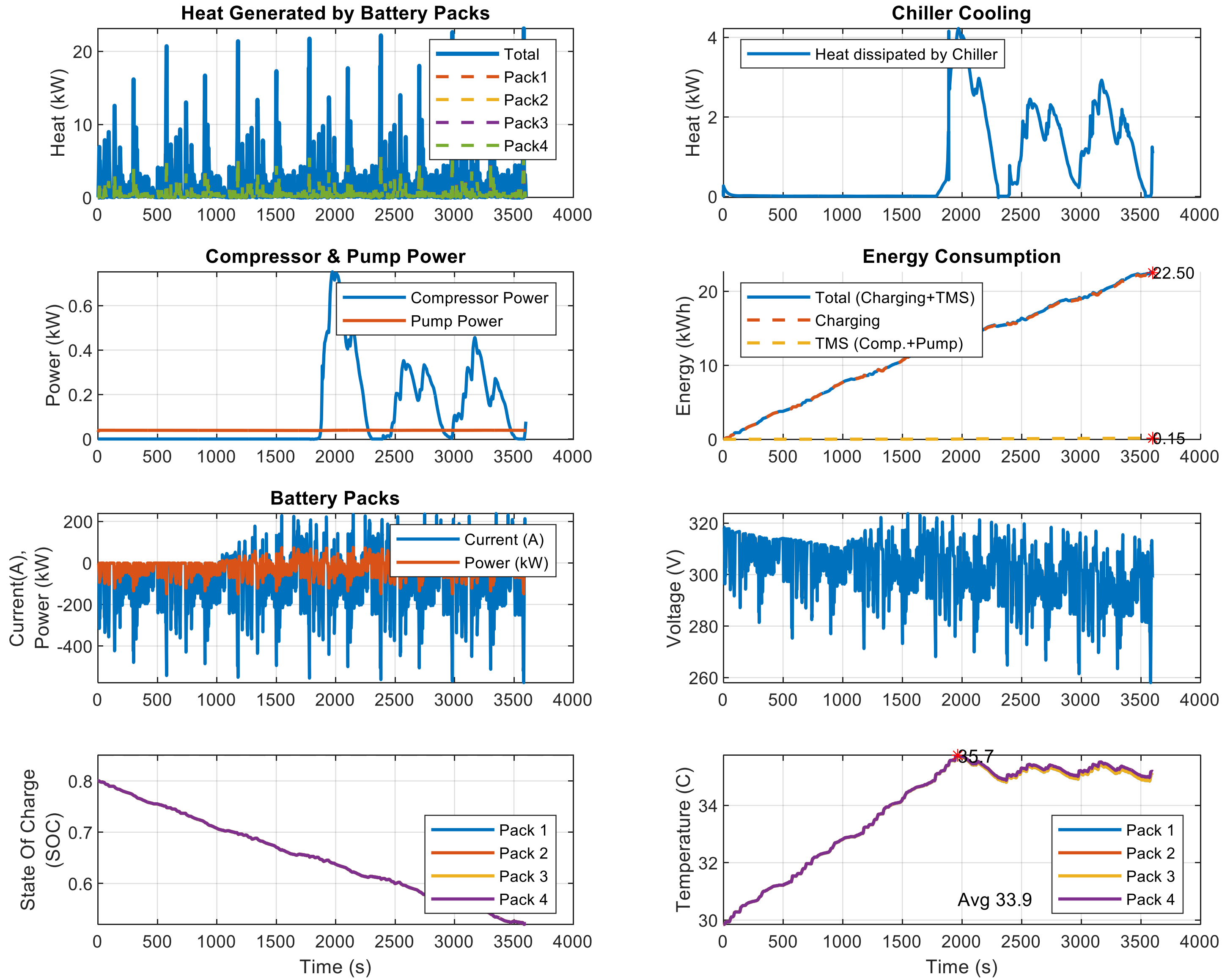
Max & Avg Cell Temp:
= 59.0°C & 45.7°C
Charging Time : 1992s
= 33.2 min
Compressor + Pump Energy :
= 3.29 kWh
Charging Energy:
= 69.19 kWh
Total Energy (Charging + Comp. + Pump):
= 72.48 kWh



Battery Discharge

Desired Battery Setpoint Temperature : **35°C**

Avg Cell Temp: **33.9°C**
Compressor + Pump Energy : **0.15 kWh**



Battery Discharge

Desired Battery Setpoint Temperature : **20°C**

Avg Cell Temp: **21.3°C**
Compressor + Pump Energy : **1.42 kWh**

Higher compressor energy consumption for lower battery setpoint temperature