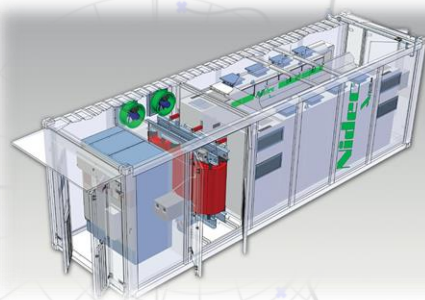




Modelos térmicos de baterias

Prof. Allan Fagner Cupertino
afcupertino@ieee.org



Tópicos a serem abordados

Por que desenvolver modelos térmicos?



Comportamento térmico de baterias;



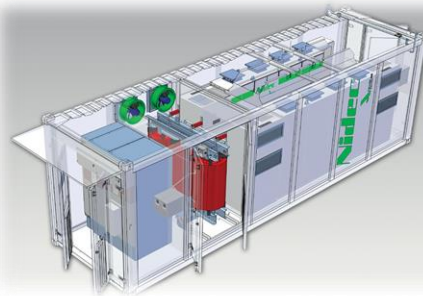
Controle de temperatura das baterias;





Por que desenvolver modelos térmicos para baterias?

Prof. Allan Fagner Cupertino
afcupertino@ieee.org



Efeito da temperatura em baterias

❑ A temperatura afeta o desempenho da bateria em diferentes escalas de tempo;

❑ Curto termo → performance elétrica;

❑ Longo termo → tempo de vida;

❑ Questões de segurança!

Low temperature (<0°C)

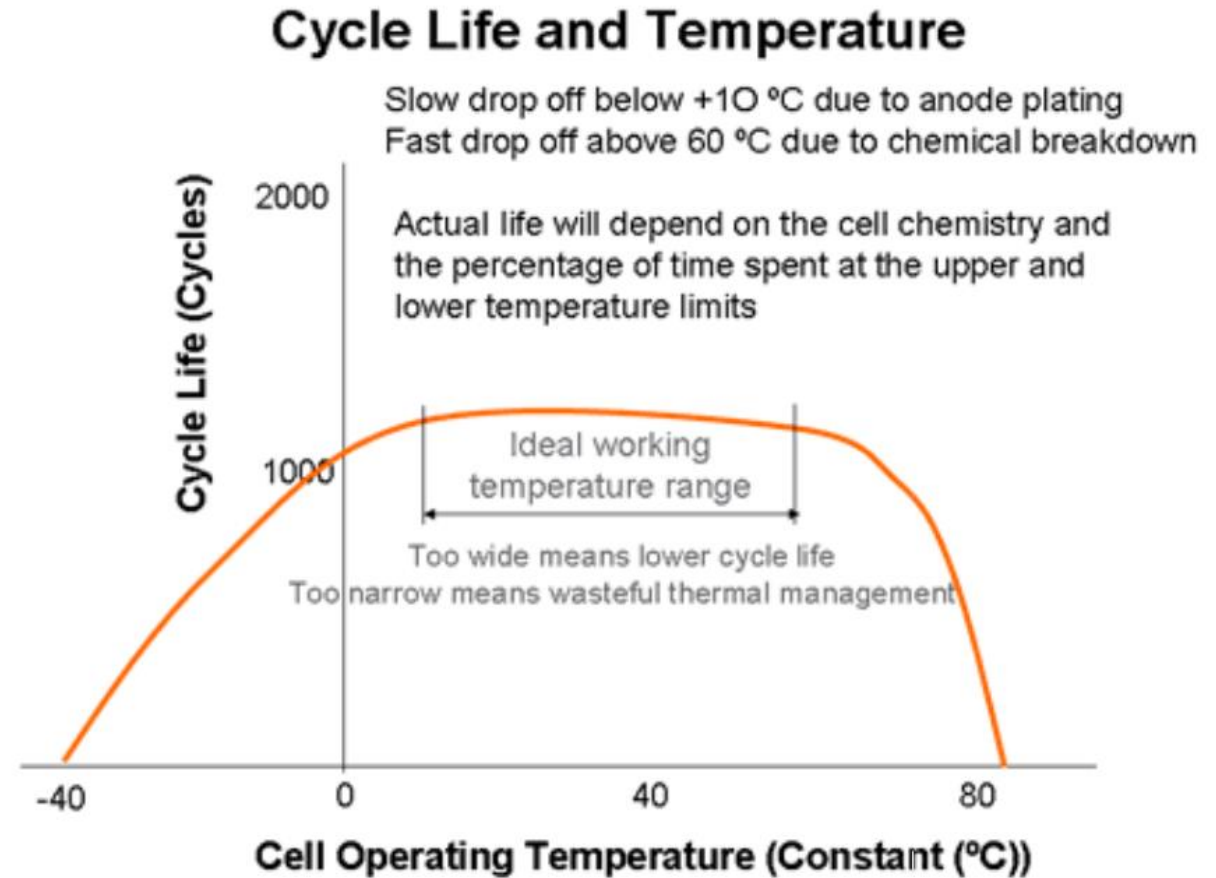
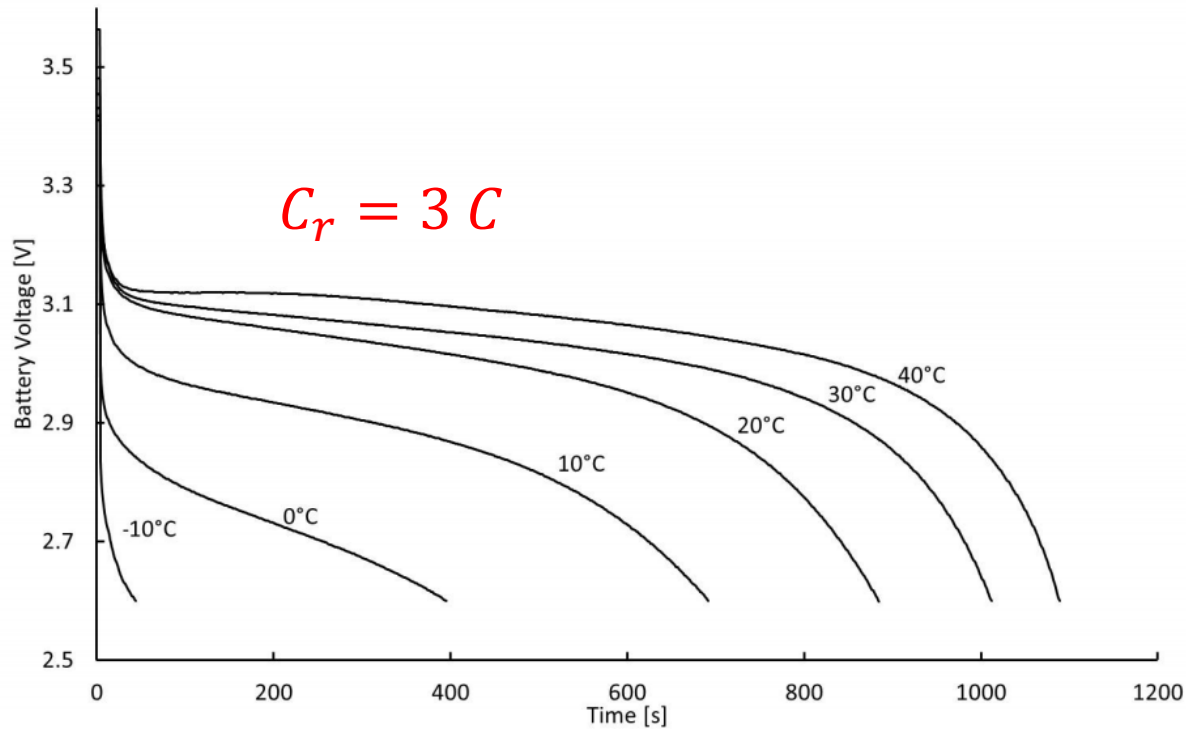
- Capacity drop
- Internal resistance increase
- Lithium plating and dendrite growths

High temperature (>40°C)

- Internal resistance decrease
- Accelerated aging phenomena
- Higher self-discharge
- Decomposition of electrolyte
- Thermal runaway, safety considerations
- Reduced life cycle

Fonte: D. I. Stroe. "Storage Systems based on Lithium-Ion Batteries for Grid Support and Automotive Applications." PhD Course. Aalborg University. 2018

Efeito da temperatura em baterias



Fontes:

- [1] K. Chen. "Heat Generation Measurements of Prismatic Lithium-Ion Batteries". Master's Thesis. University of Waterloo, 2013.
- [2] S. Sepasi. "Adaptive state of charge estimation for battery packs". PhD Thesis. 2014

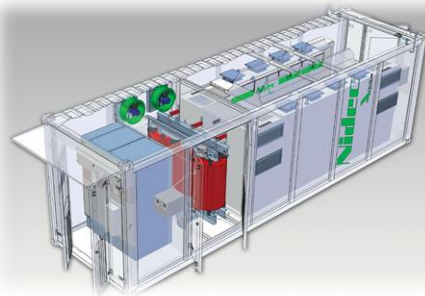
Efeito da temperatura em baterias – Avalanche Térmica



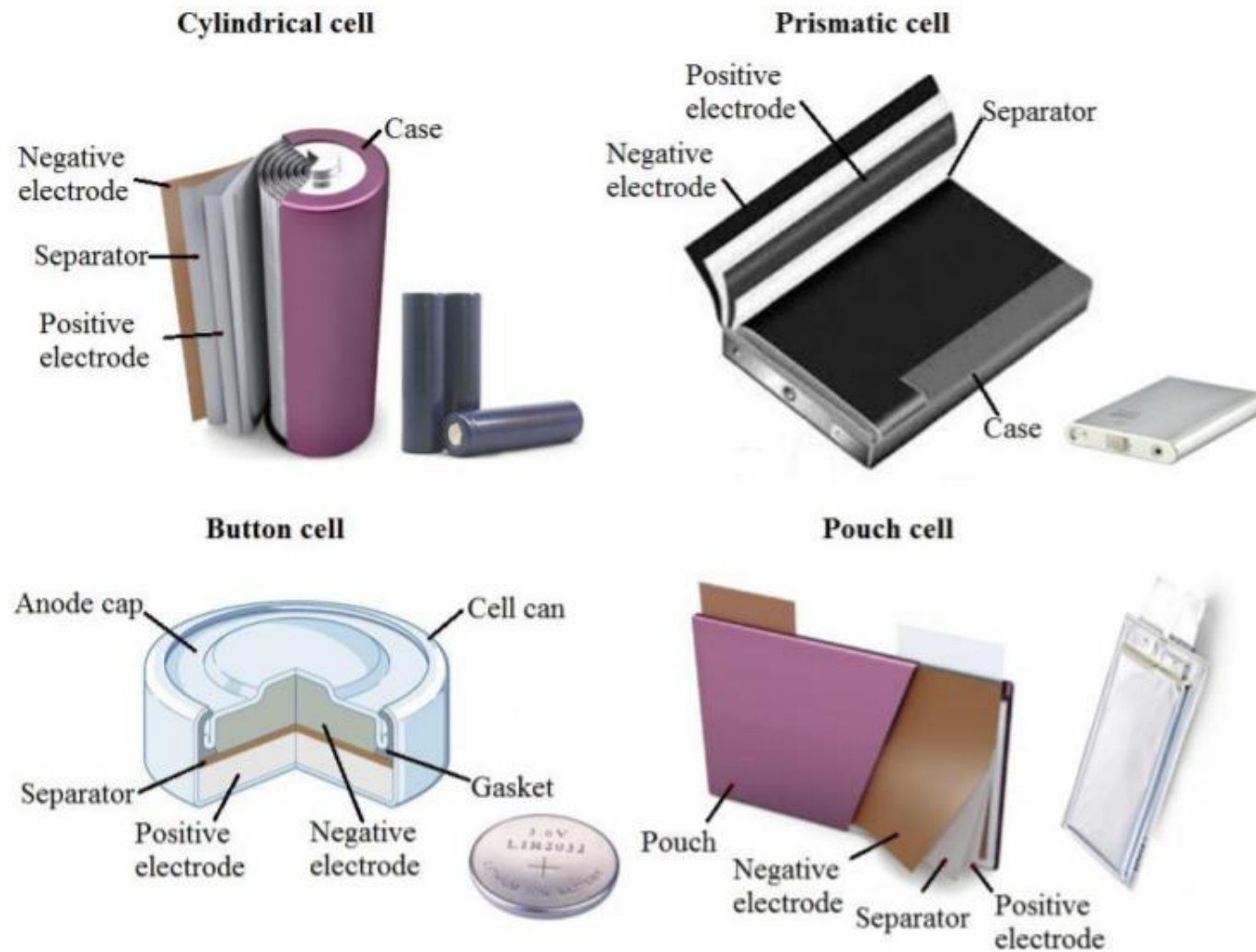


Comportamento térmico de baterias

Prof. Allan Fagner Cupertino
afcupertino@ieee.org

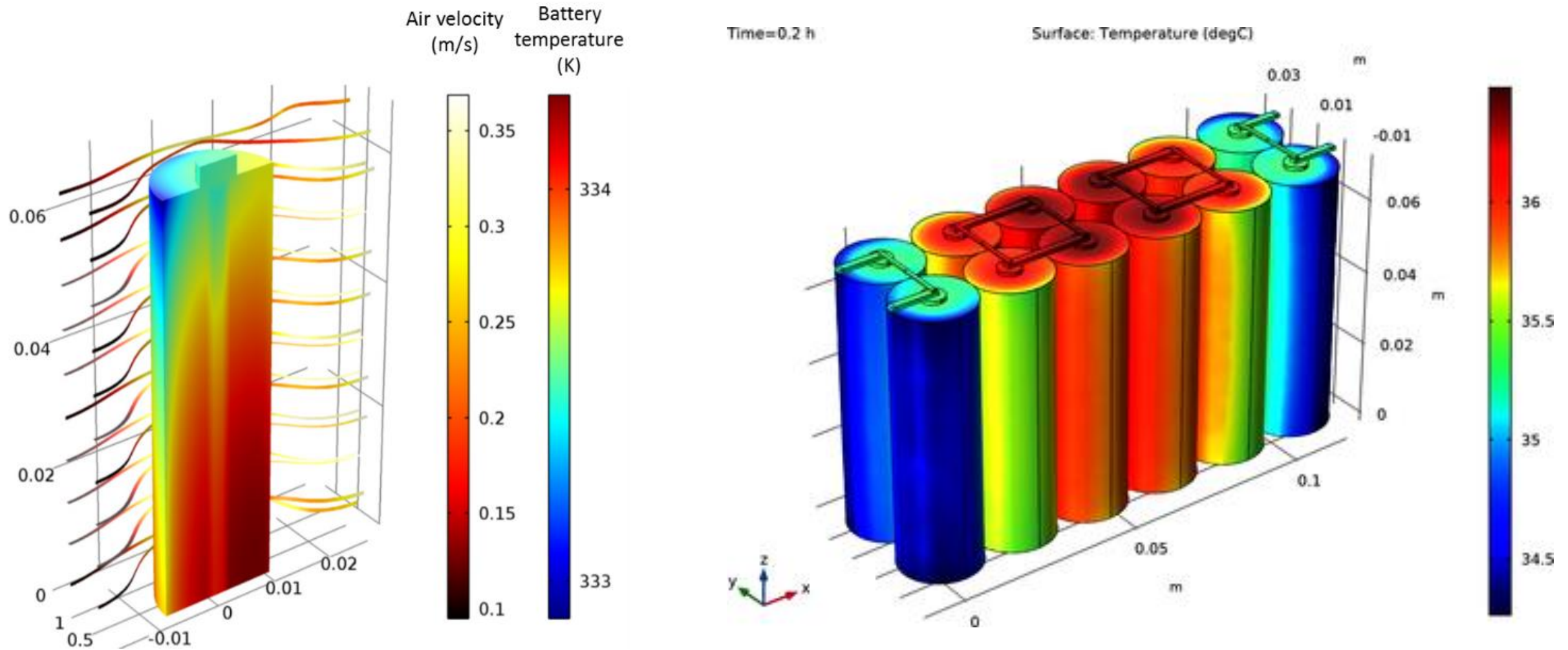


Comportamento térmico → Encapsulamento



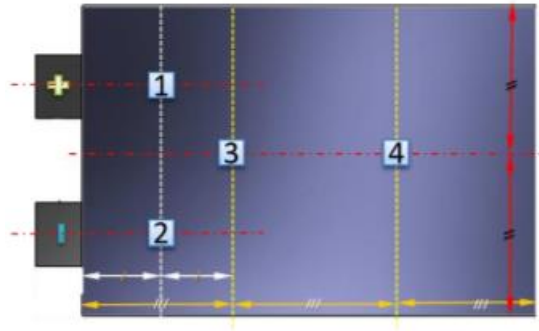
Fonte: K. Murashko. "Thermal modelling of commercial lithium-ion batteries". Ph.D. Thesis. Lappeenranta University of Technology, 2016.

Comportamento térmico



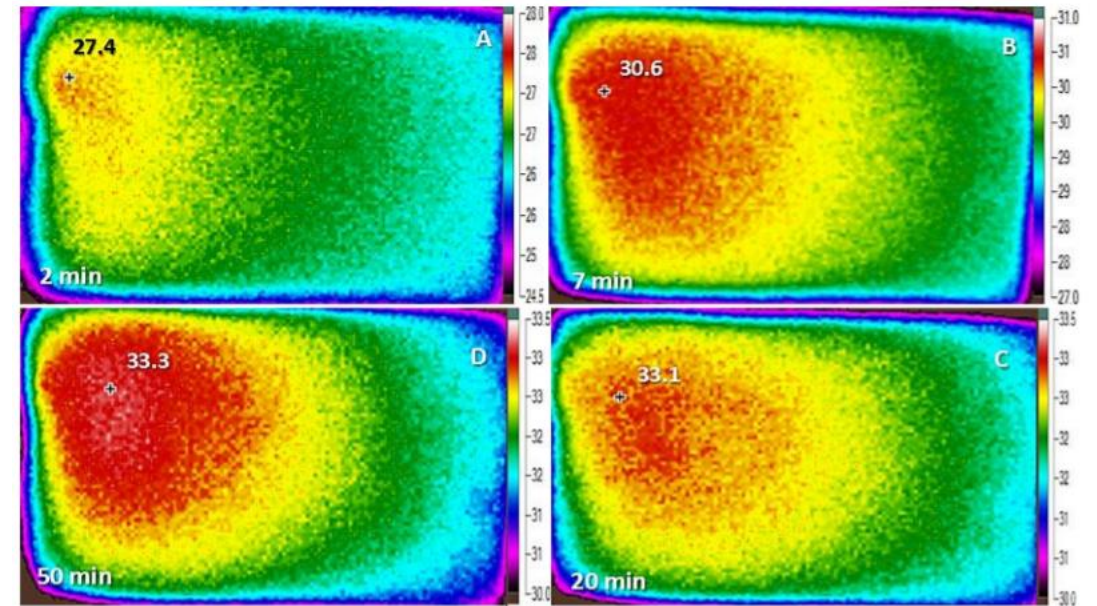
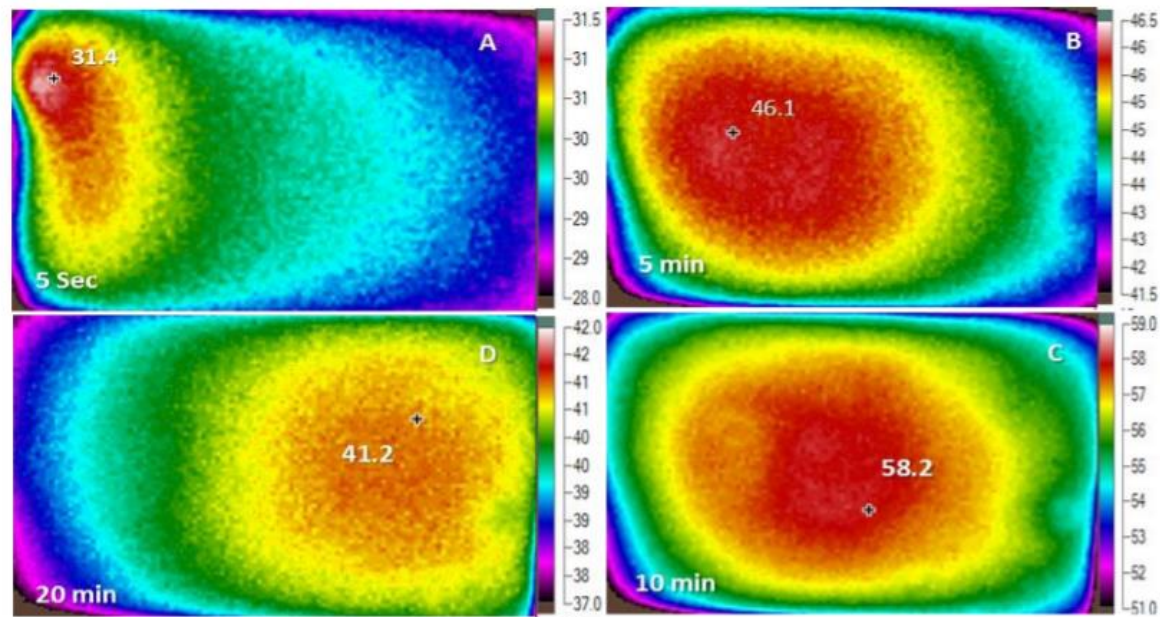
Fonte: Comsol. "Thermal modeling of a Cylindrical Lithium-Ion Battery in 3D"

Impacto do perfil de operação na distribuição de temperatura



Descarga $\rightarrow C_r = 5 C$

Corrente pulsada

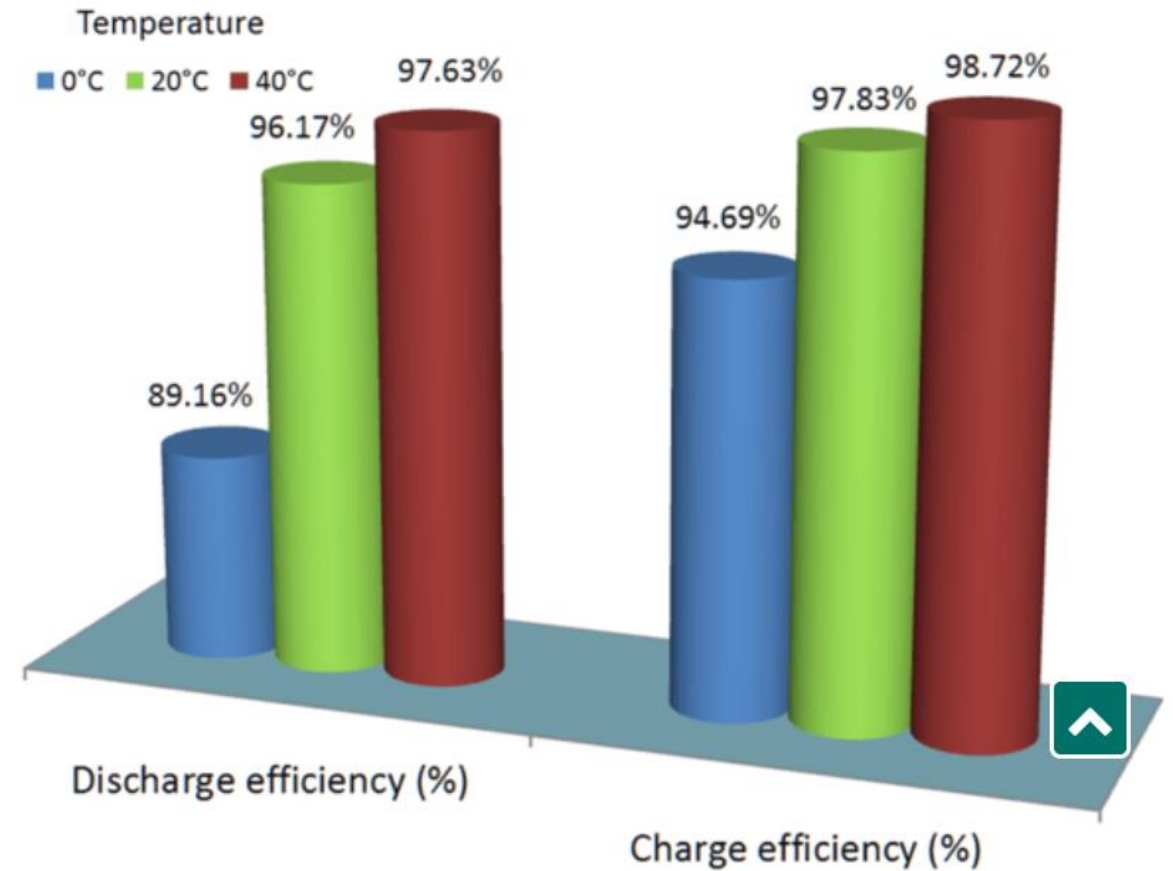
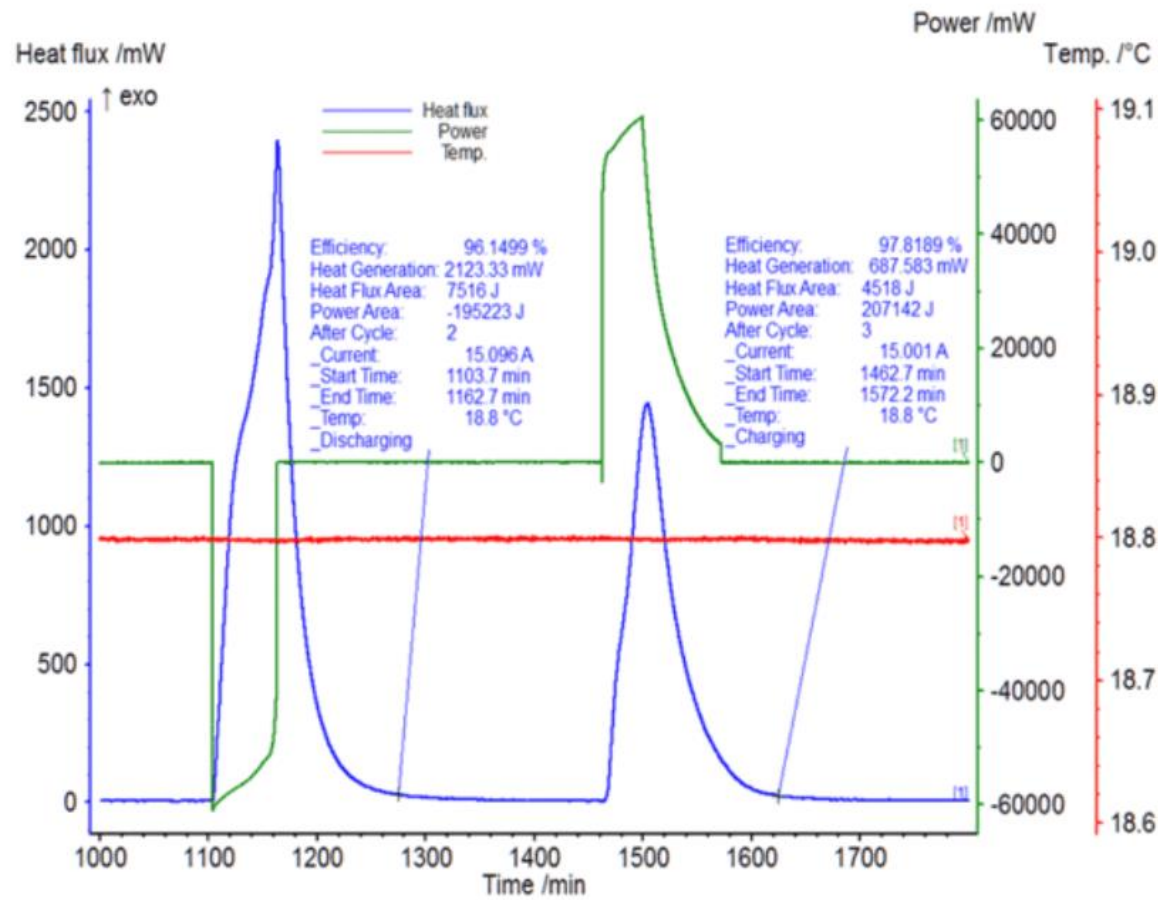


Fonte: S. Goutam, et al. Surface temperature evolution and the location of maximum and average surface temperature of a lithium-ion pouch cell under variable load profiles. European Electric Vehicle Congress. 2014

Geração de calor na bateria

- Efeito Joule;
- Operação eletroquímica;
- Geração de calor por ser diferente em diferentes pontos da célula;
- Dependente da química e da construção da bateria;
- Valores inicial e final do estado de carga;
- Temperatura da bateria;
- Perfil de operação (C-rate).

Geração de calor na bateria



Fonte: Netsch Application examples.

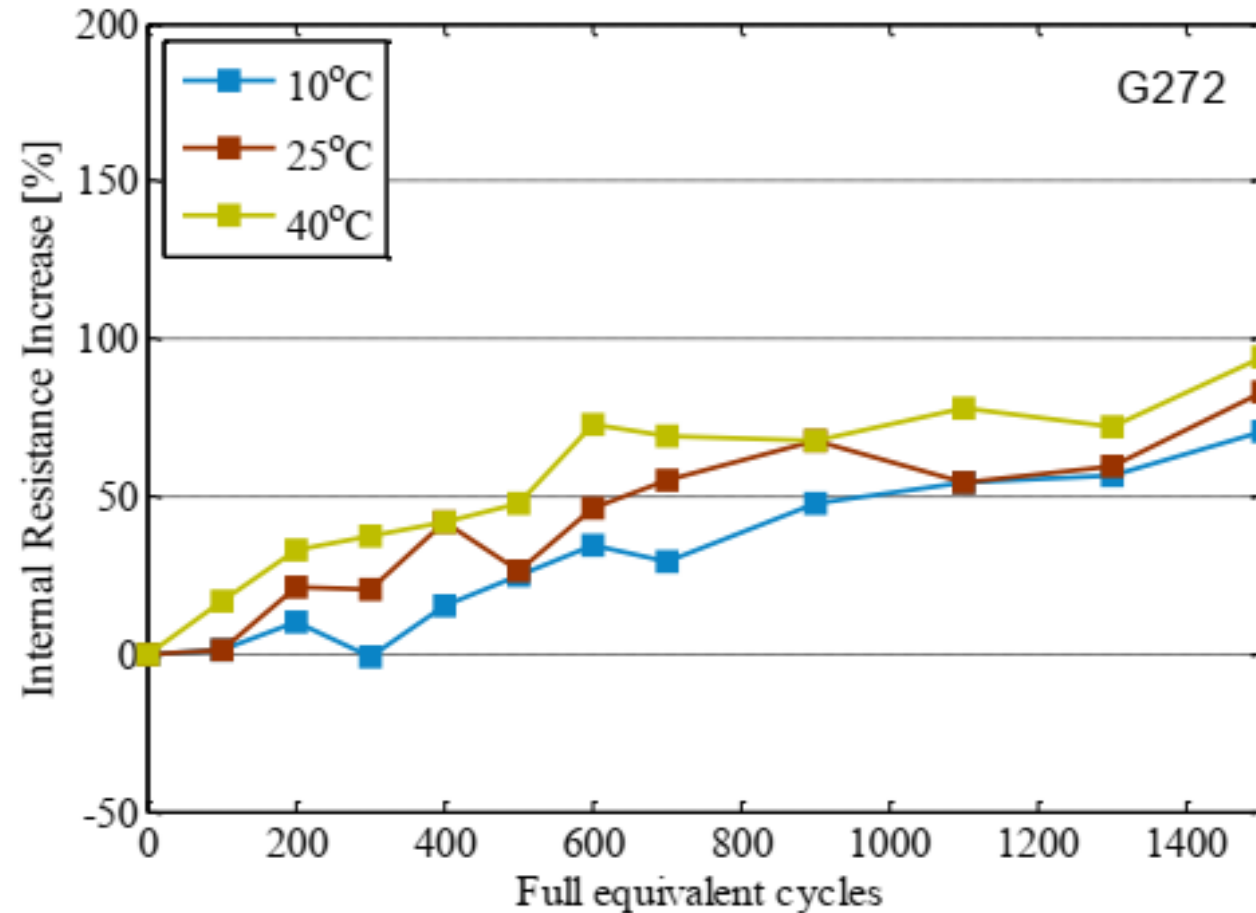
Geração de calor na bateria

- ❑ Equação de Bernardi (1985);
- ❑ Baterias de Lítio com encapsulamento Pouch;
- ❑ Princípio do balanço de energia;

$$\dot{q}_t = i (V_{oc} - V_t) - i T \frac{\partial V_{oc}}{\partial T} \Leftrightarrow \dot{q}_t = R_{in} i^2 - i T \frac{\partial V_{oc}}{\partial T} = \dot{q}_{joule} + \dot{q}_{entropia}$$

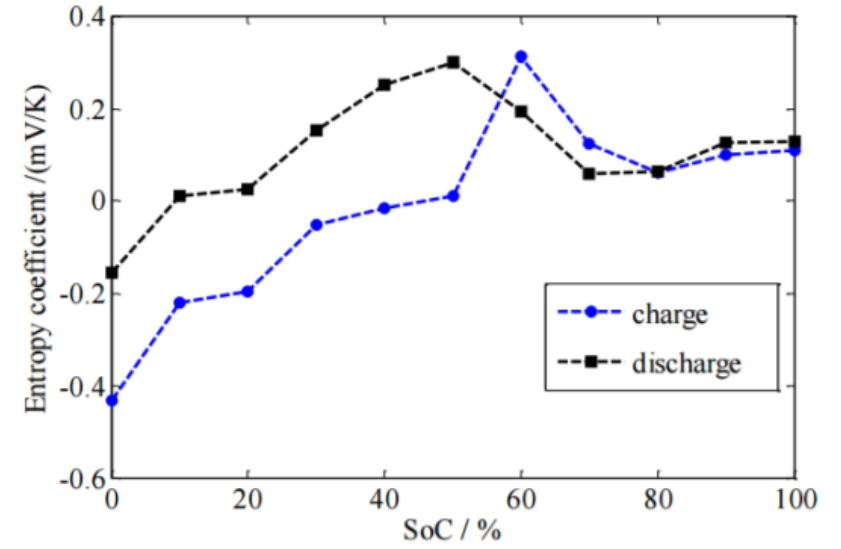
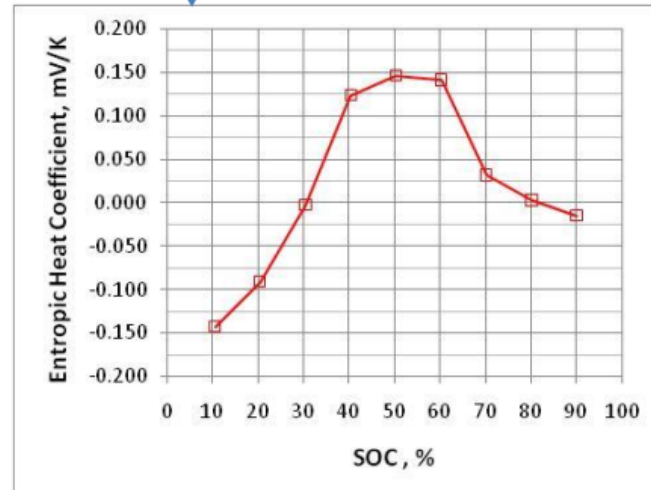
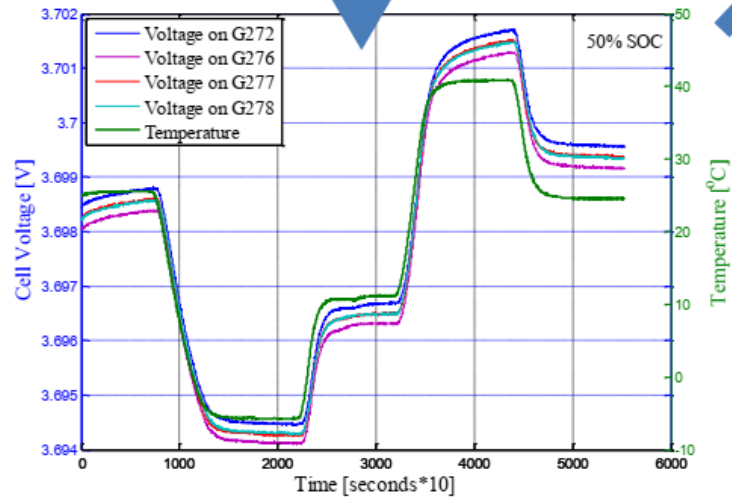
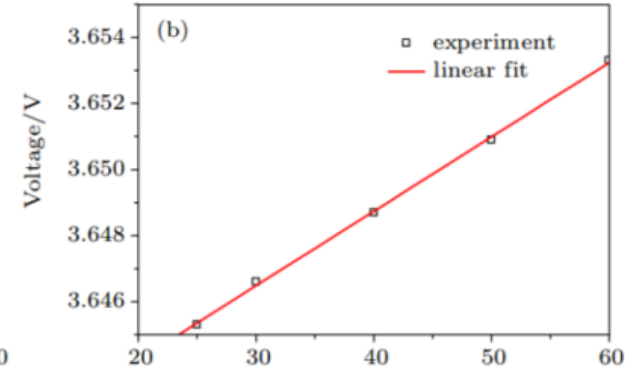
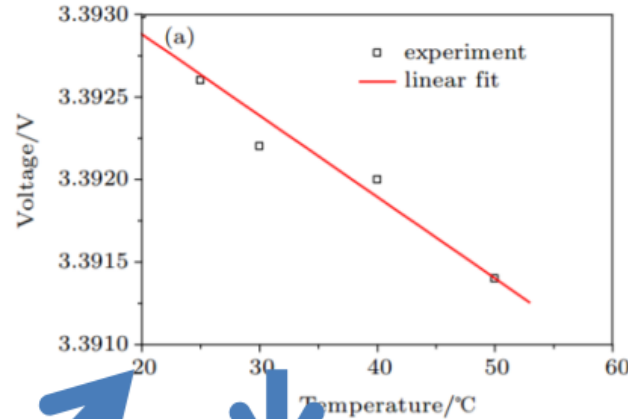
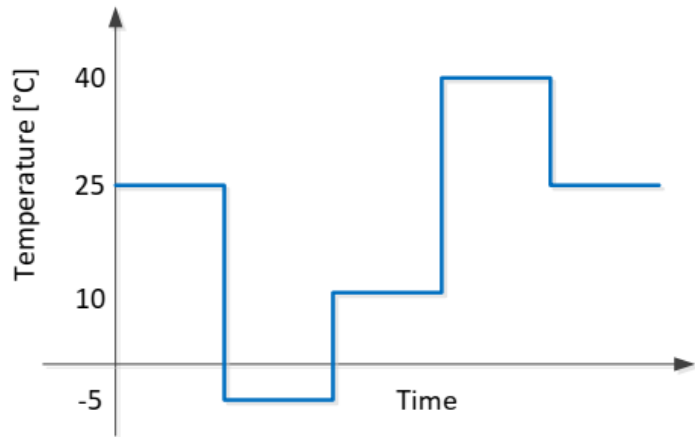
- ❑ Calor gerado devido a polarização → sempre positivo;
- ❑ Calor gerado pela variação de entropia → pode ser positivo ou negativo;
- ❑ Assume baixa diferença de temperatura ao longo da bateria (1-4 °C).

Resistência interna R_{in}



Fonte: T. Stanciu et. al., Performance Degradation of Thermal Parameters during Cycle Ageing of High Energy Density Ni-Mn-Co based Lithium-Ion Battery Cells. ECCE. 2016

EHC – Entropic heat coefficient $\frac{\partial V_{oc}}{\partial T}$

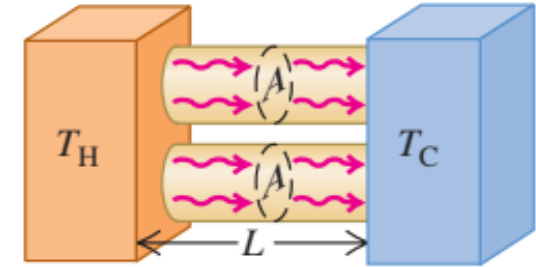


Fonte: D. I. Stroe. “Storage Systems based on Lithium-Ion Batteries for Grid Support and Automotive Applications.” PhD Course. Aalborg University. 2018

Mecanismos de transferência de calor

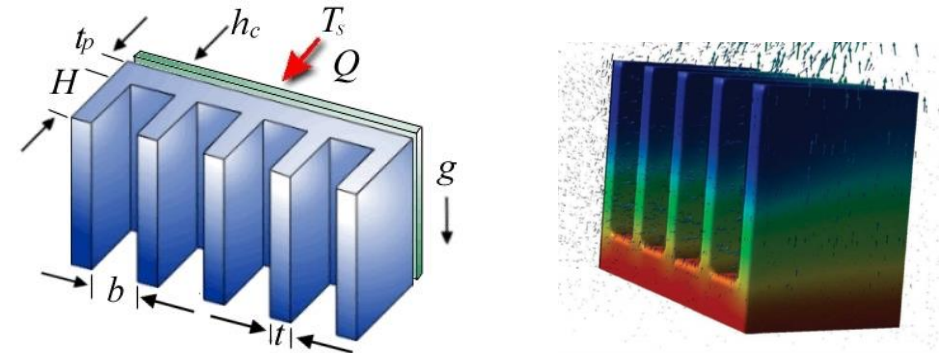
☐ Condução;

$$Q_{cond} = \frac{kA}{L} (T_H - T_L)$$



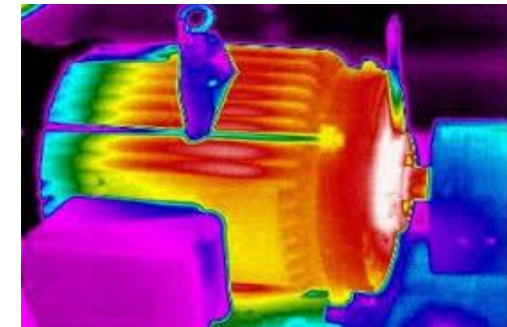
☐ Convecção;

$$Q_{conv} = h A (T_H - T_\infty)$$



☐ Irradiação.

$$Q_{irrad} = A e \sigma (T_H^4 - T_\infty^4)$$



Condutividade Térmica

- ❑ Define a capacidade de transporte de energia como o resultado da diferença de temperatura;
- ❑ Unidade: $W/(m K)$;
- ❑ Depende da temperatura mas tem uma baixa dependência com o estado de carga da bateria;
- ❑ Obtida experimentalmente:

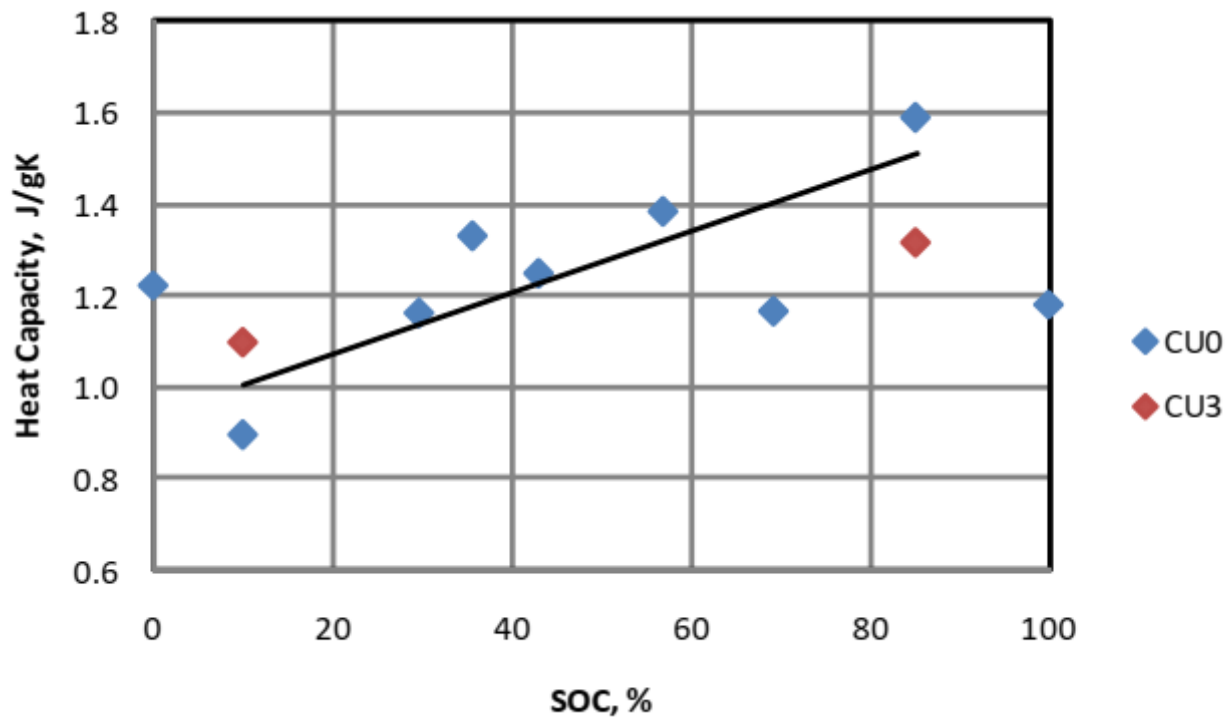
$$k = \frac{qT}{\Delta T}$$

Calor específico

- ❑ Determina a dinâmica térmica da bateria;
- ❑ Quantidade de calor para aquecer um 1 Kg do material em 1 °C;
- ❑ Depende do estado de carga da bateria;
- ❑ Determinado a partir de ensaios Calorimétricos;

$$C = \frac{Q}{m (\Delta T)}$$

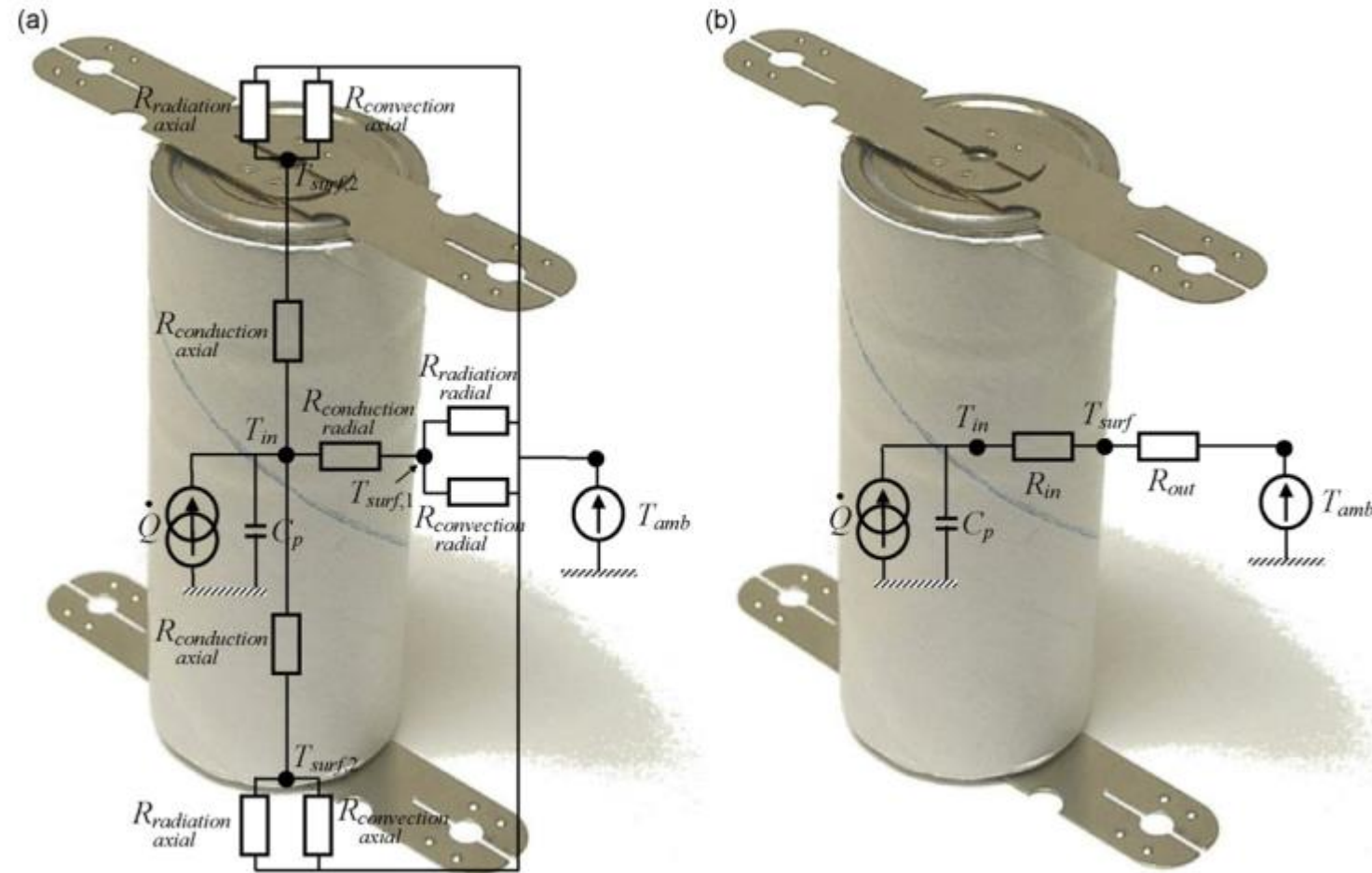
Comportamento do calor específico



Battery	Application	Average Battery Temp (°C)	Heat Capacity (J/kg/°C)
NiMH – 20 Ah	HEV	33.2	677.4
Li Ion - 6 Ah	HEV	33.1	795
Lithium Ion Polymer – 4 Ah	EV	18	1011.8
NiMH – 90 Ah	EV	33.9	787.5
Ni MH – 6.5 Ah	HEV	32.9	521
VRLA – 16.5 Ah	HEV	32	660

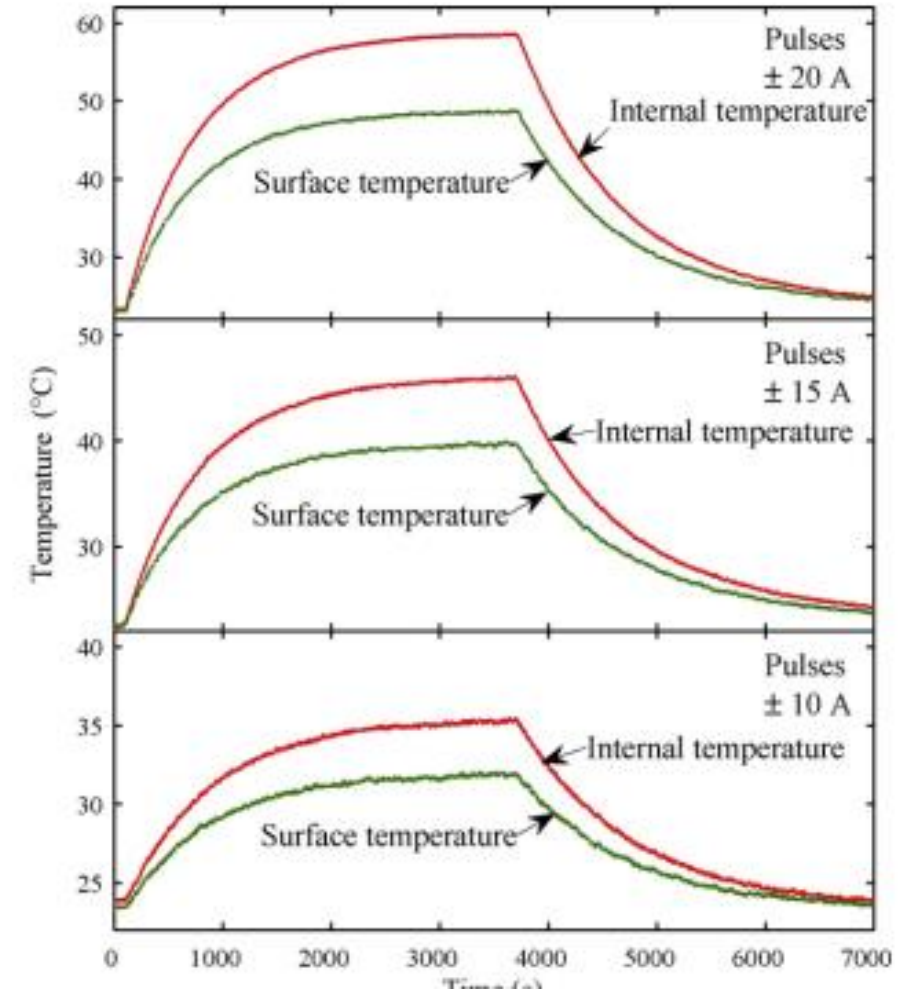
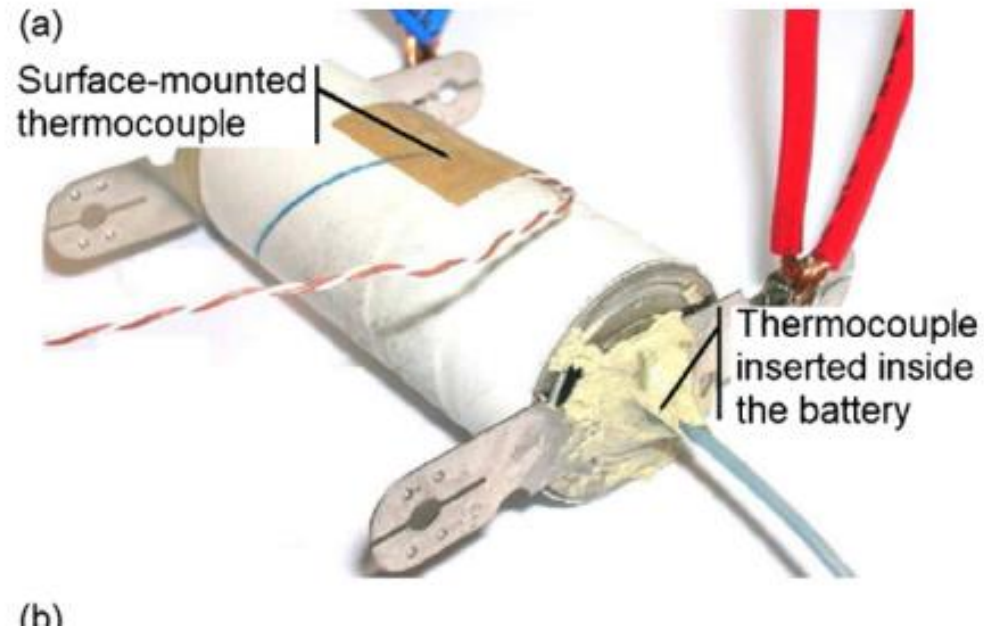
Fonte: Batteries2020, EPE2016 Workshop.

Exemplo: Modelo unidimensional



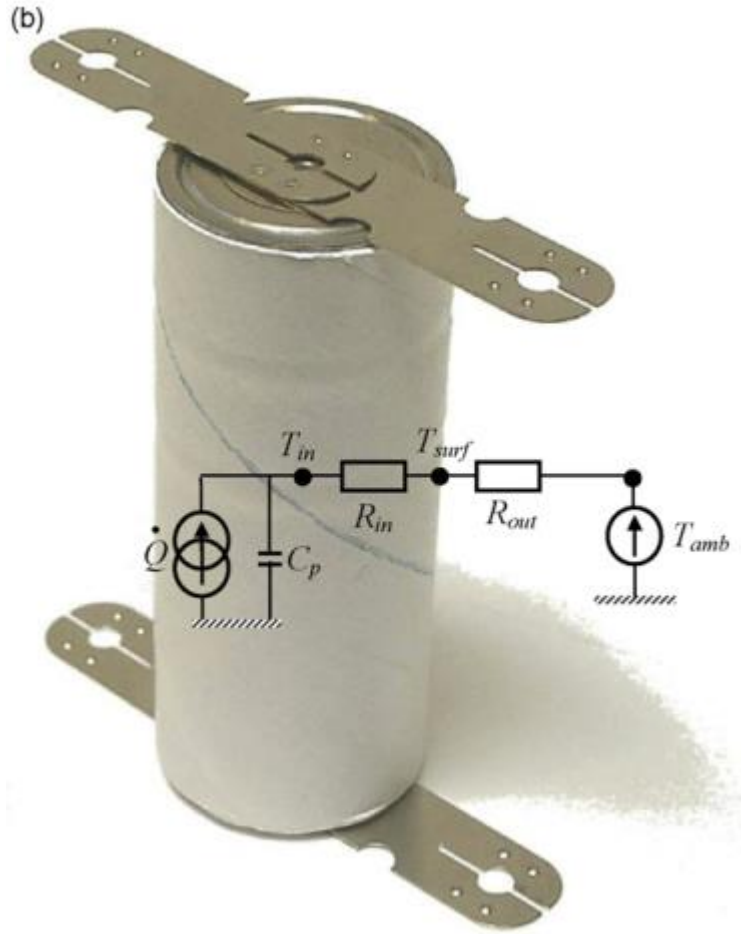
Fonte: C. Forgez et.al. "Thermal modeling of a cylindrical LiFePO₄/graphite lithium-ion battery". Journal of Power Sources. 2010.

Exemplo: Modelo unidimensional



Fonte: C. Forgez et.al. "Thermal modeling of a cylindrical LiFePO₄/graphite lithium-ion battery". Journal of Power Sources. 2010.

Exemplo: Modelo unidimensional



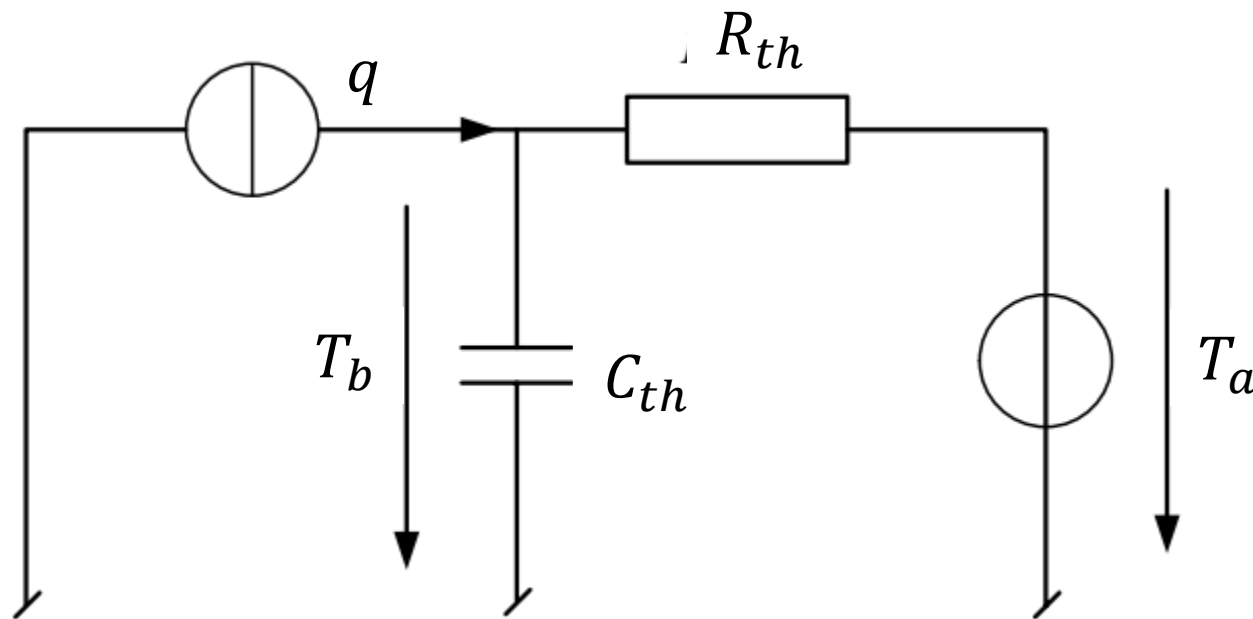
Pulse	± 10 A	± 15 A	± 20 A
$R_{out}(\text{K W}^{-1})$	9.12	9.08	8.44
$R_{in}(\text{K W}^{-1})$	3.273	3.386	3.20
R_{in}/R_{out}	0.359	0.373	0.379
$C_p(\text{JK}^{-1})$	73.2	77.7	77.9

Fonte: C. Forgez et.al. "Thermal modeling of a cylindrical LiFePO₄/graphite lithium-ion battery". Journal of Power Sources. 2010.

Circuito elétrico equivalente a dinâmica térmica

□ Calor Gerado = calor armazenado + calor conduzido.

$$q = mC_b \frac{dT_b}{dt} + \frac{kA}{L} (T_b - T_a) \Leftrightarrow q = C_{th} \frac{dT_b}{dt} + R_{th} (T_b - T_a)$$



Fonte: A. Rufer. "Energy Storage: Systems and Components," CRC Taylor & Francis Group, 2018.

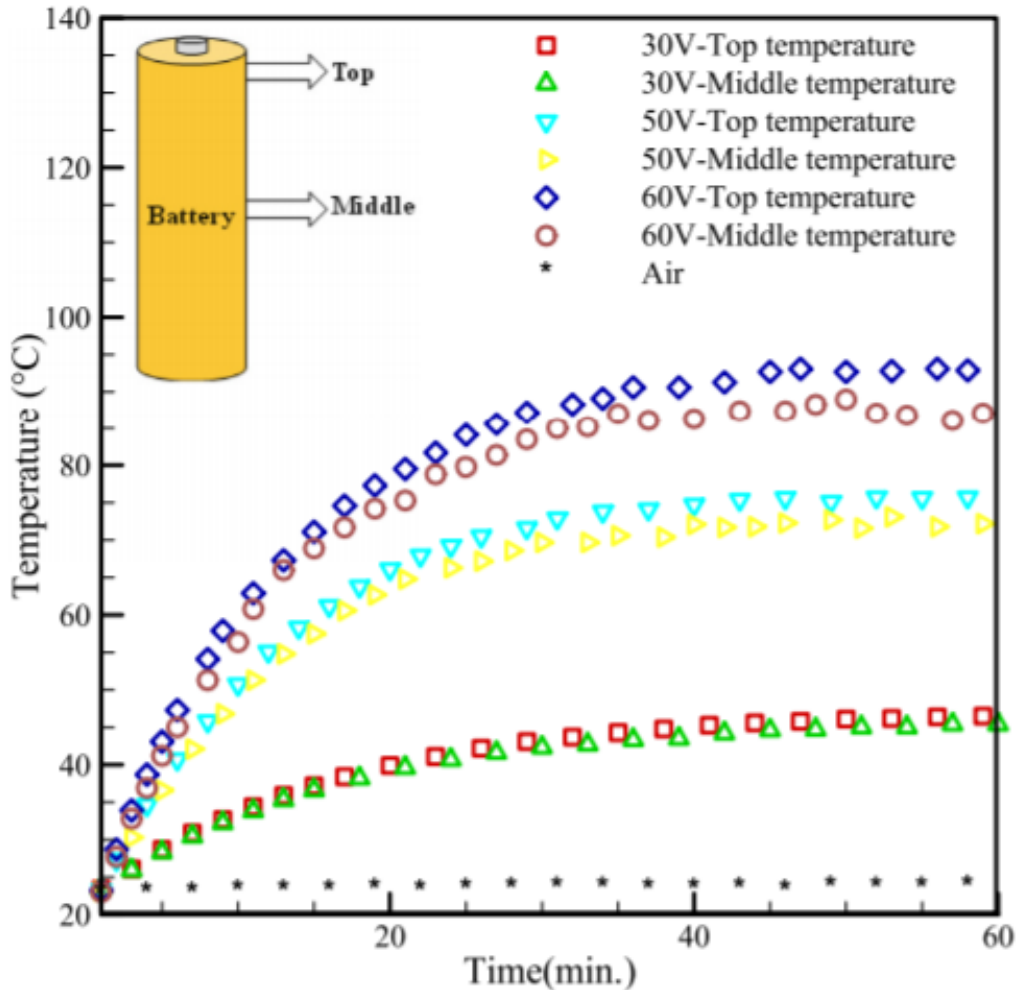
Calor específico ponderado

$$C_b = \sum x_i C_i$$

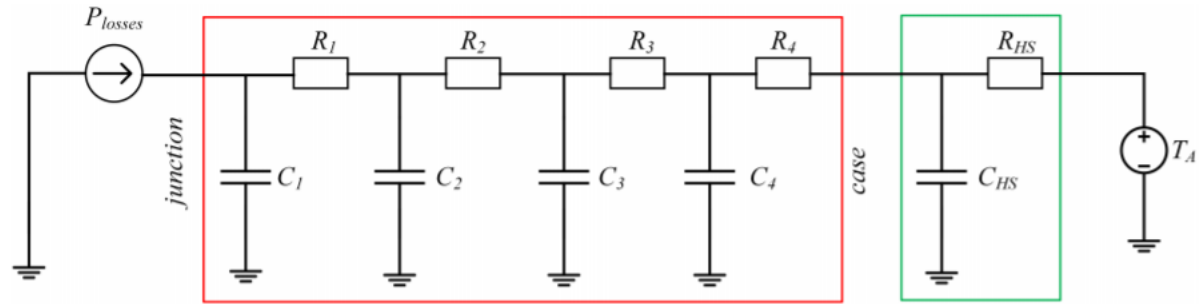
Composition of the LFP Cell	Mass Fraction x_i [%]	C_{vi} [J/kg K]
Aluminum	0.18	900
Copper	0.11	385
Separator (PP, PE, PVDF, PET)	0.07	1551
LFP (LiFePO_4)	0.24	841
Graphite	0.19	700
Electrolyte	0.2	1375
Stainless steel	0.01	477
Entire specific heat capacity	1	927

Fonte: A. Rufer. "Energy Storage: Systems and Components," CRC Taylor & Francis Group, 2018.

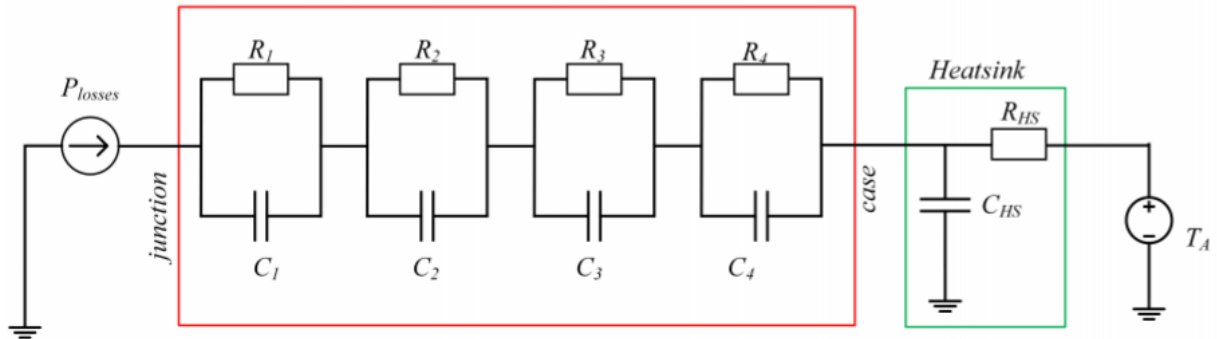
Modelos térmicos – Cauer e Foster



Modelo de Cauer

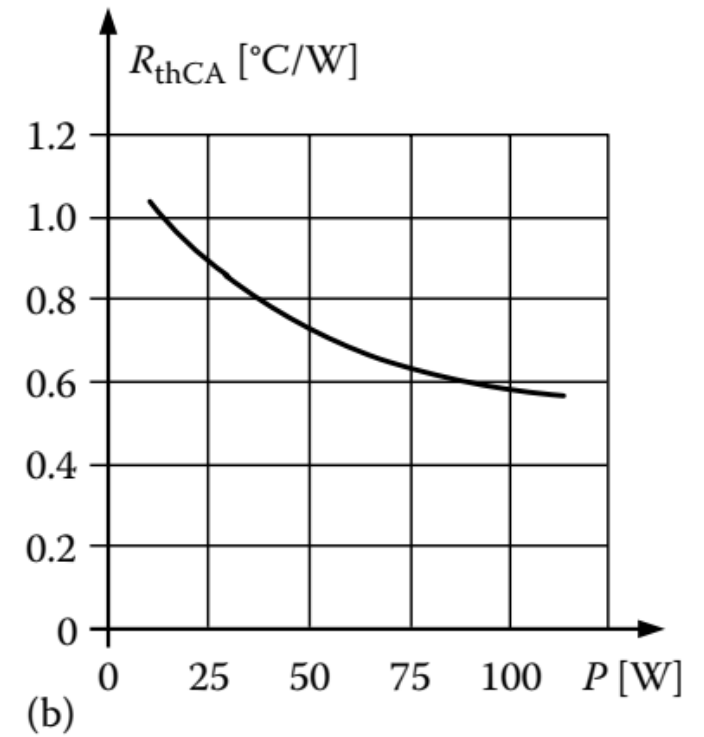
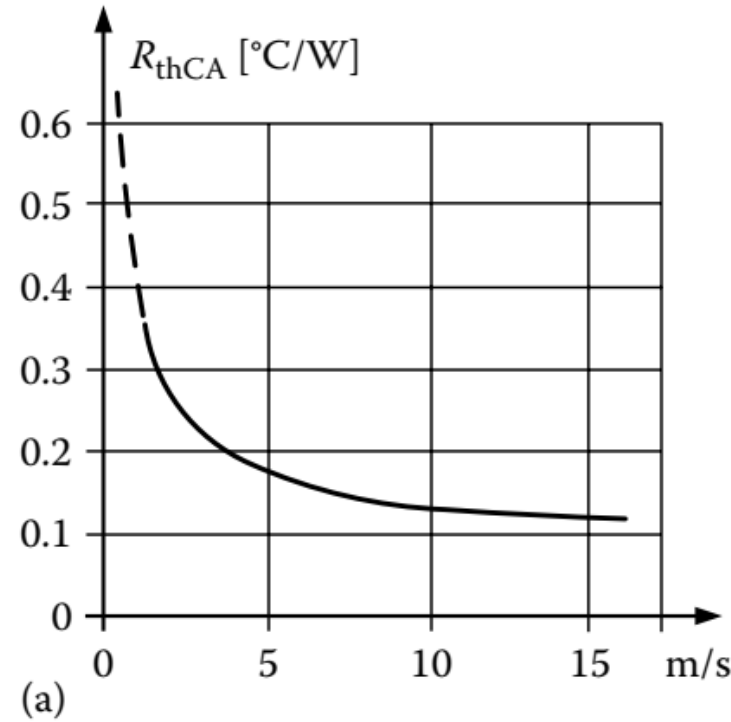
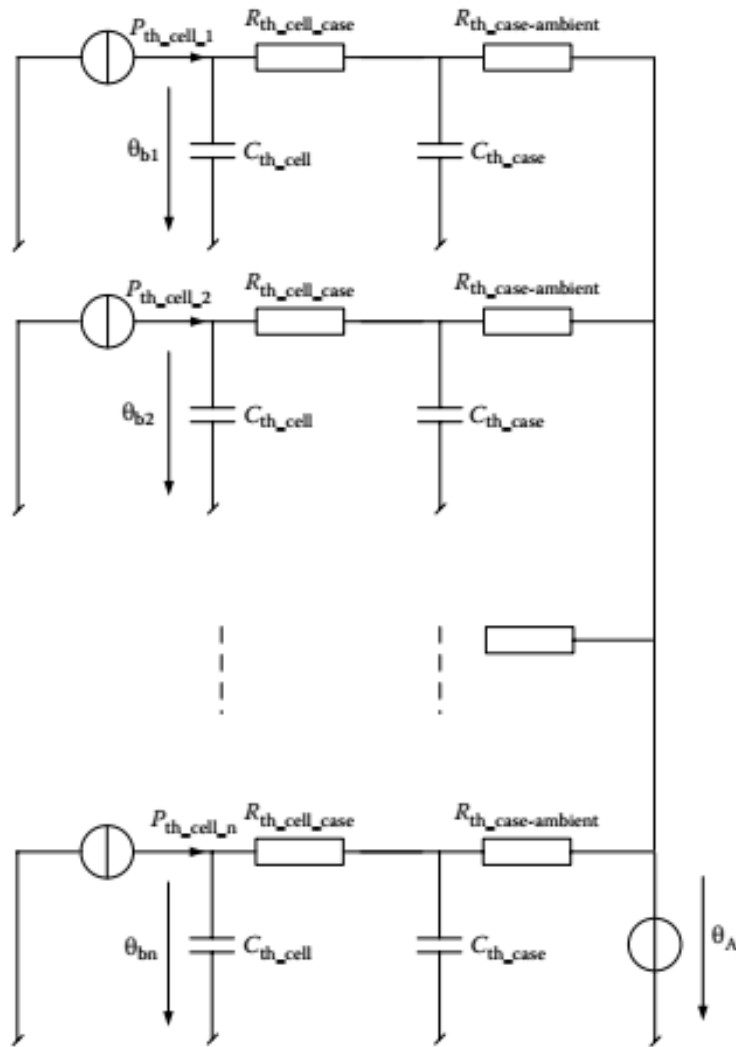


Modelo de Foster



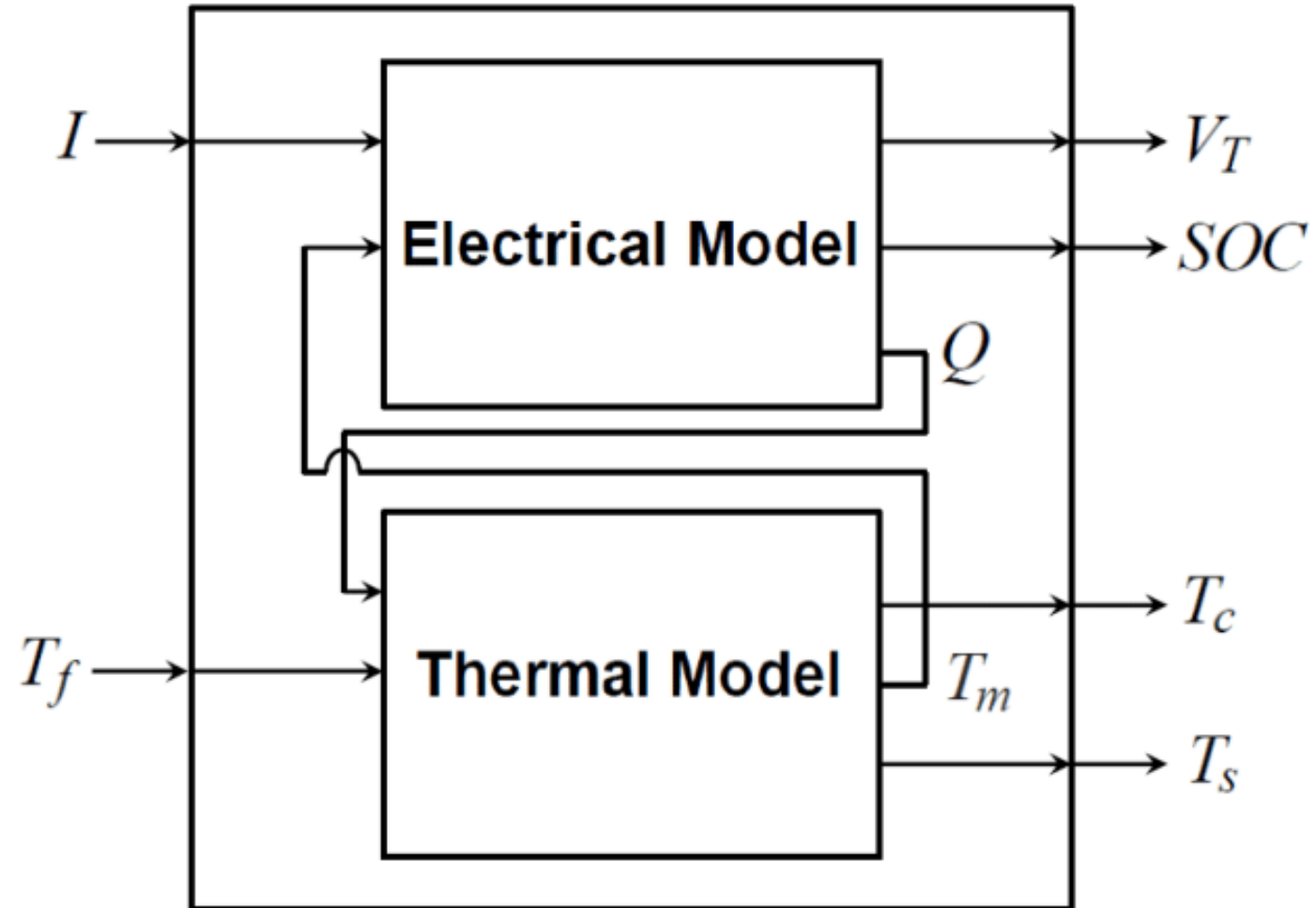
Fonte: Y. Lyu et.al. “Electric vehicle battery thermal management system with thermoelectric cooling”. Energy Reports. 2019.

Simulação de um Rack de baterias



Fonte: A. Rufer. "Energy Storage: Systems and Components," CRC Taylor & Francis Group, 2018.

Modelo eletrotérmico de uma bateria

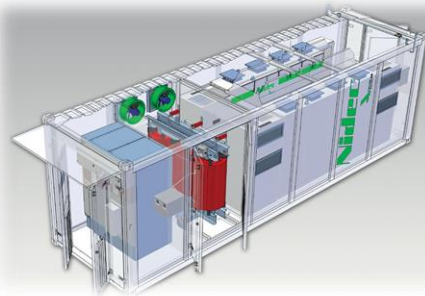


Fonte: H. E. Perez et. al. "Parameterization and Validation of an Integrated Electro-Thermal Cylindrical LFP Battery Model". 2012.



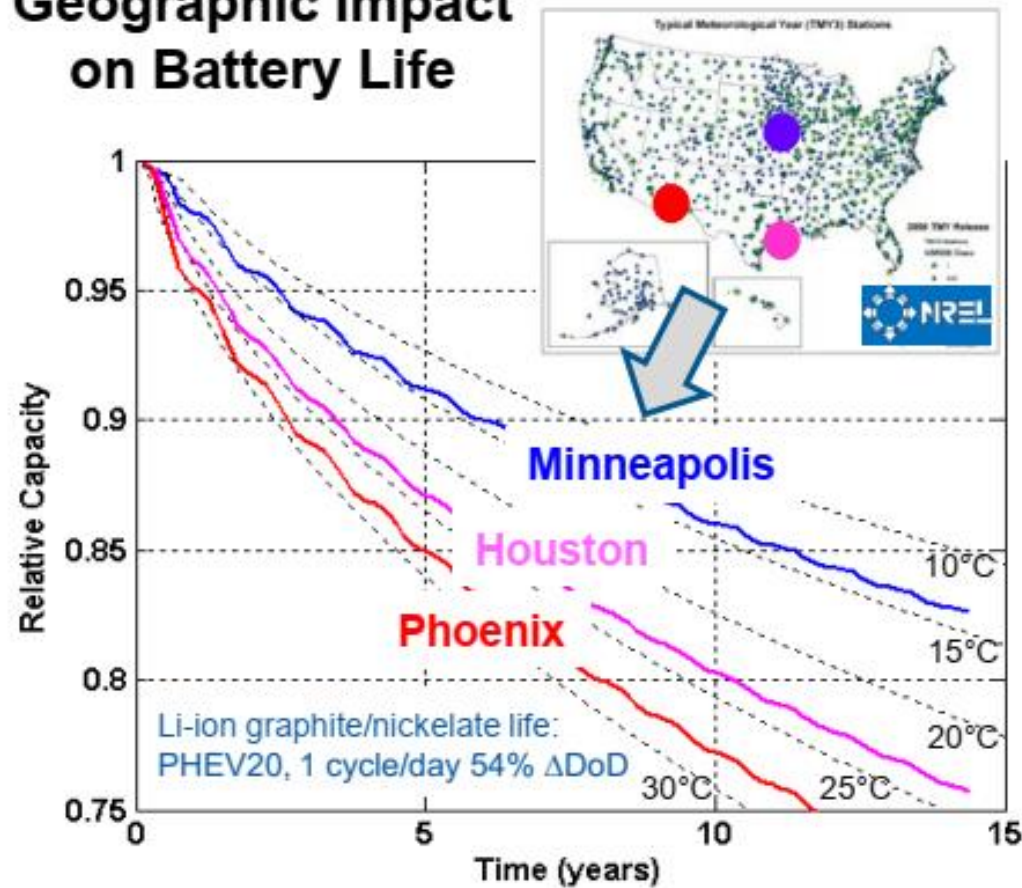
Controle de temperatura de baterias

Prof. Allan Fagner Cupertino
afcupertino@ieee.org

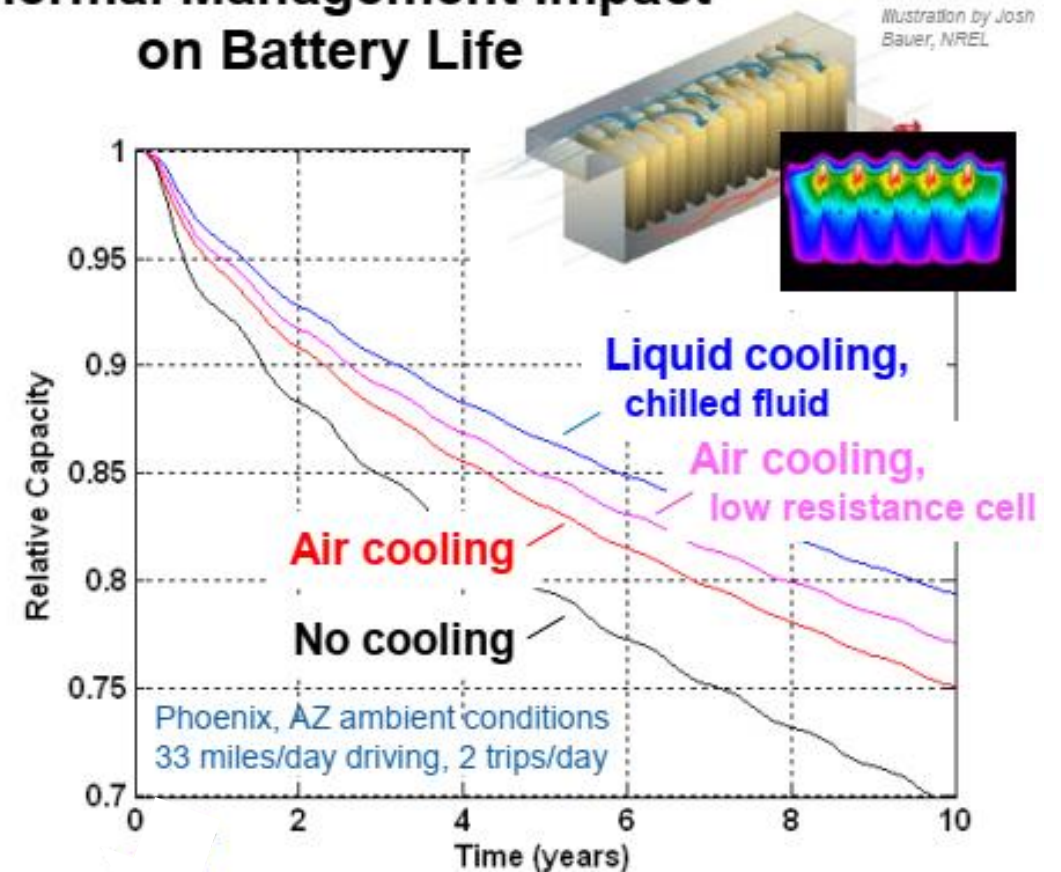


Efeito da temperatura na degradação

Geographic Impact on Battery Life

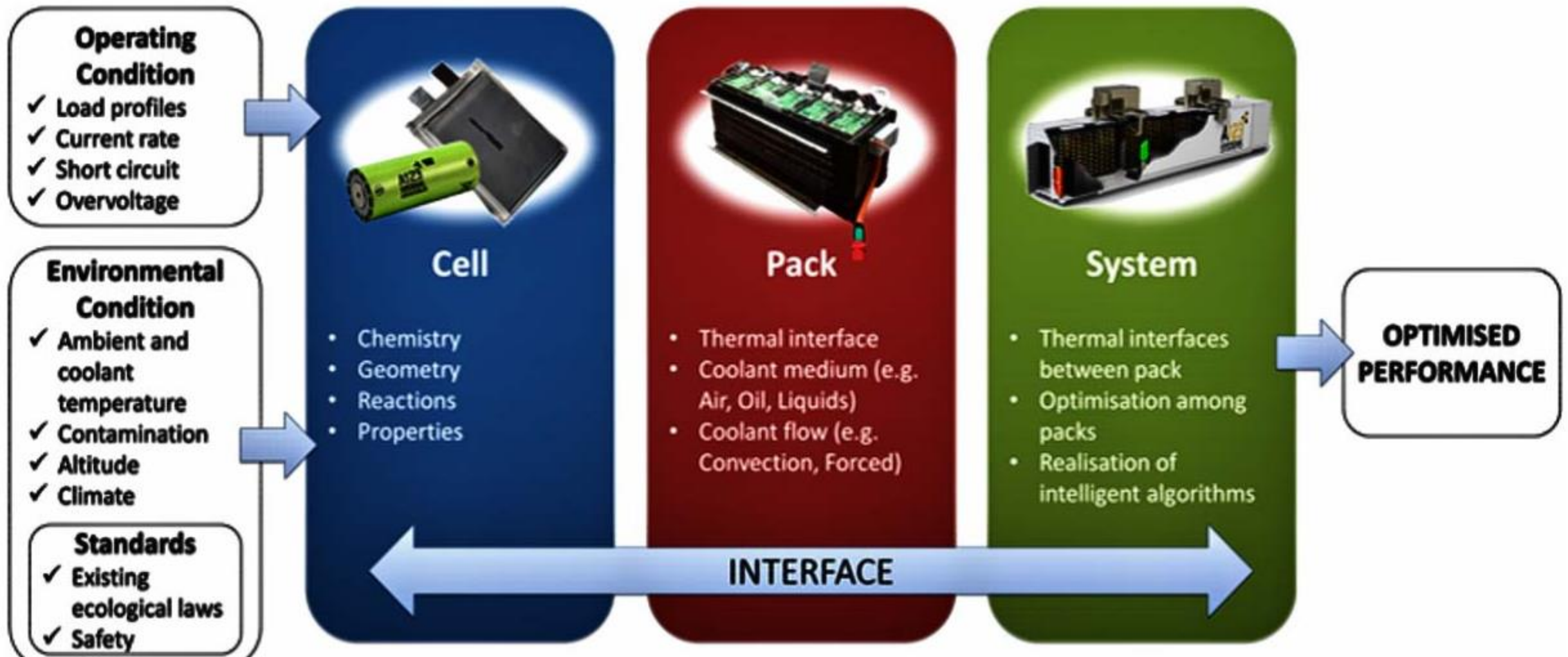


Thermal Management Impact on Battery Life



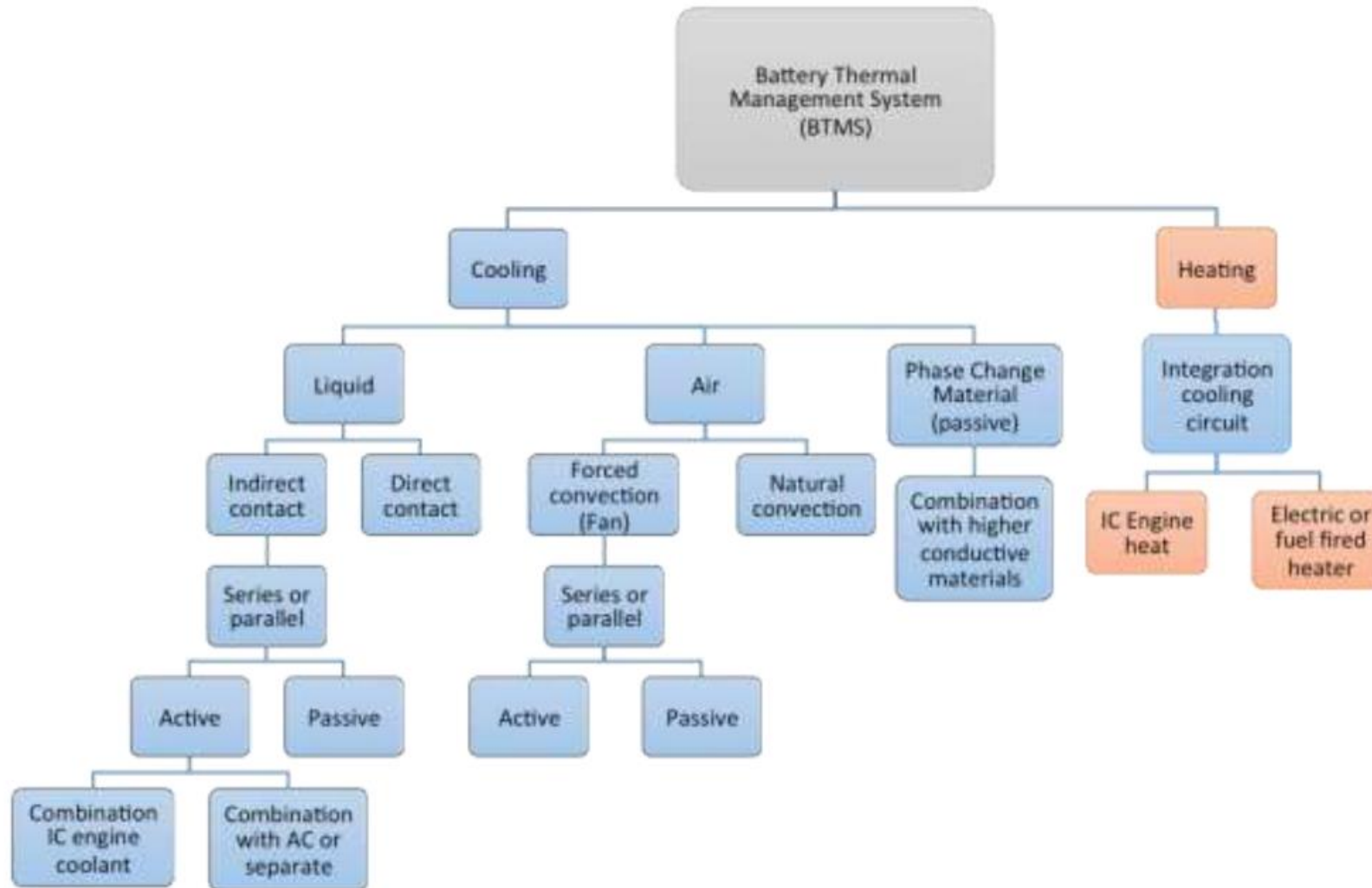
Fonte: NREL.

Sistema de monitoramento e manejo térmico



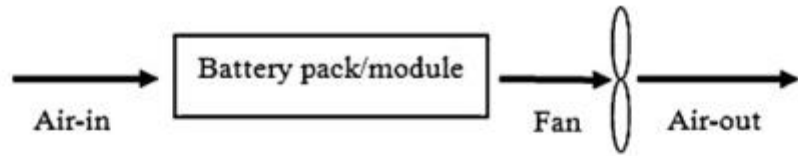
Fonte: M. R. Khan et. al. "Towards an Ultimate Battery Thermal Management System: A Review," Batteries MDPI, 2016.

Sistema de monitoramento e manejo térmico

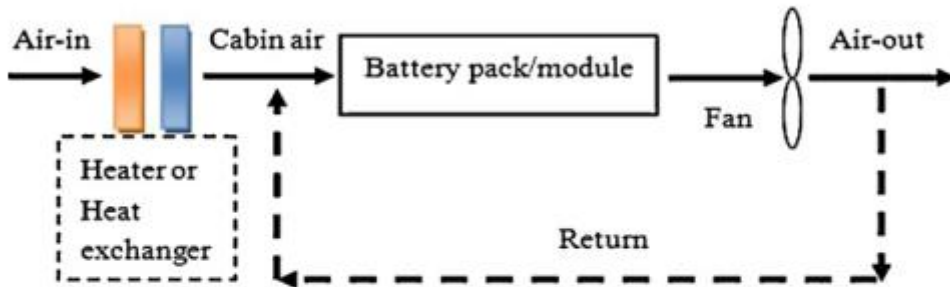


Fonte: Ahmadou Samba. "Battery Electrical Vehicles-Analysis of Thermal Modelling and Thermal Management". Ph.D. Thesis. Université de caen Basse Normandie. 2015.

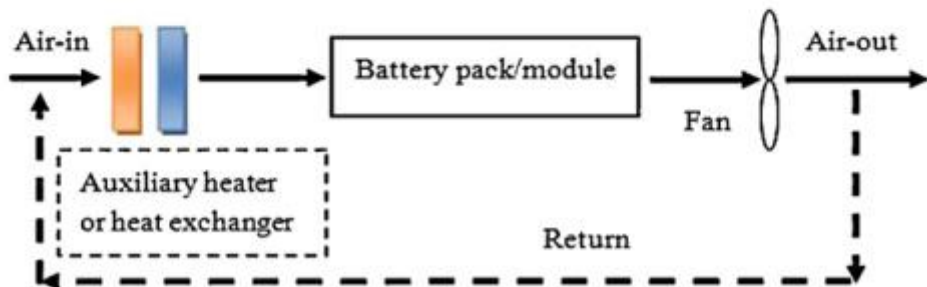
Sistema de monitoramento e manejo térmico



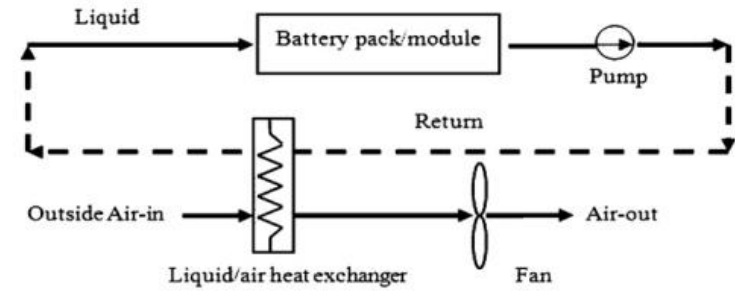
(a) Passive air cooling



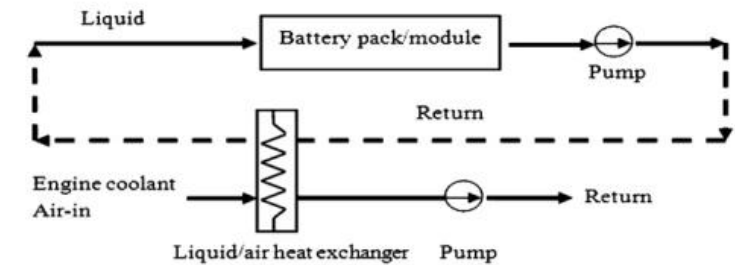
(b) Passive air cooling/heating



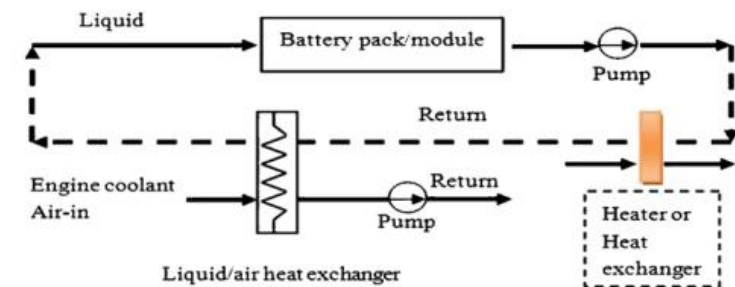
(c) Active air cooling/heating



(a) Passive liquid cooling



(b) Active moderate cooling/heating



Fonte: Z. Rao and S. Wang, "A review of power battery thermal energy management". Renewable and Sustainable Energy Reviews. 2011.

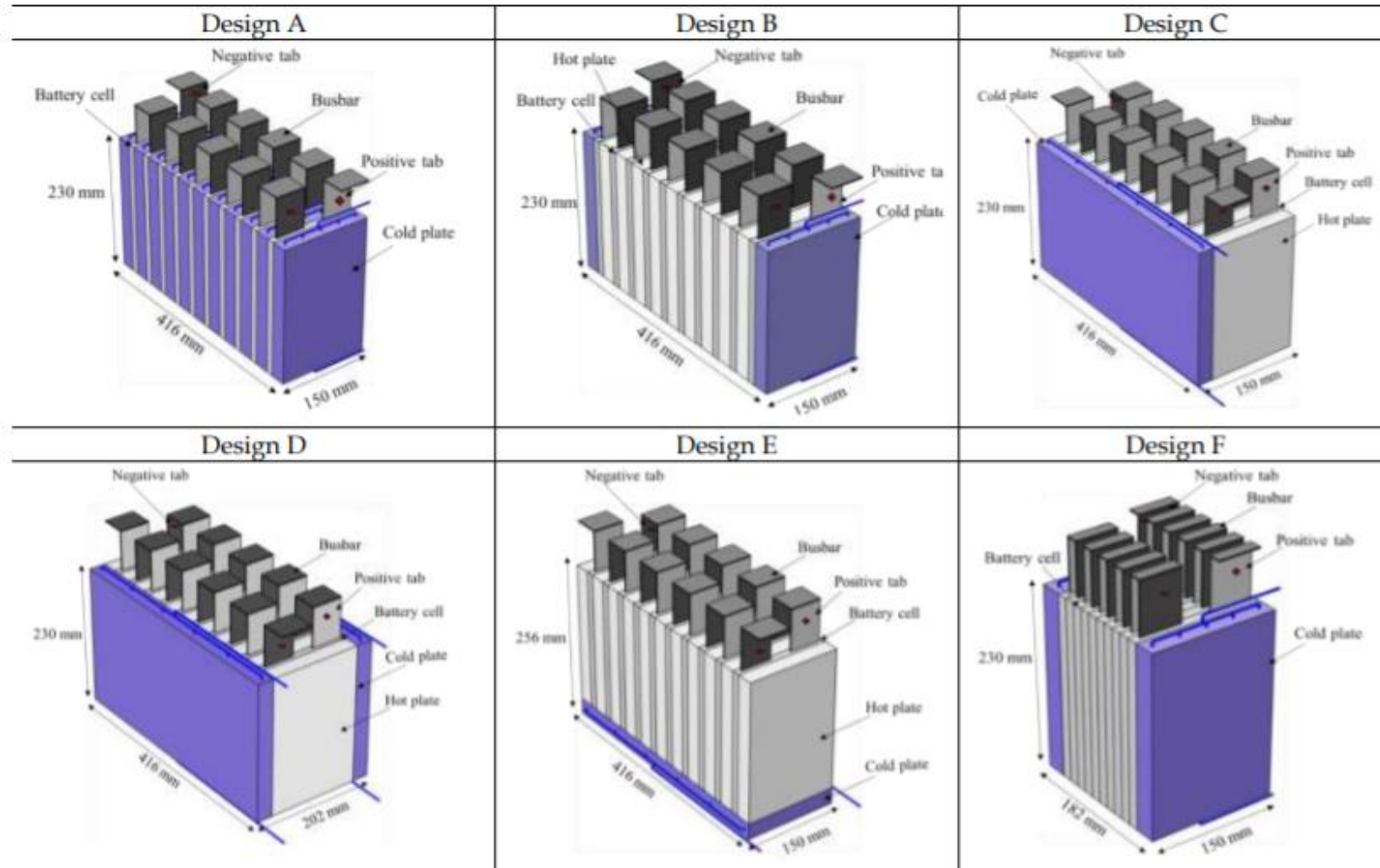
Sistema de monitoramento e manejo térmico

	Air forced	Liquid	Heat pipe	PCM	Thermoelectric	Cold plate
Ease of use	Easy	Difficult	Moderate	Easy	Moderate	Moderate
Integration	Easy	Difficult	Moderate	Easy	Moderate	Moderate
Efficiency	Low	High	High	High	Low	Medium
Temperature drop	Small	Large	Large	Large	Medium	Medium
Temperature distribute	Uneven	Even	Moderate	Even	Moderate	Moderate
Maintenance	Easy	Difficult	Moderate	Easy	Difficult	Moderate
Life	≥20 years	3–5 years	≥20 years	≥20 years	1–3 years	≥20 years
First cost	Low	High	High	Moderate	High	High
Annual cost	Low	High	Moderate	Low	High	Moderate

PCM = protection circuit module

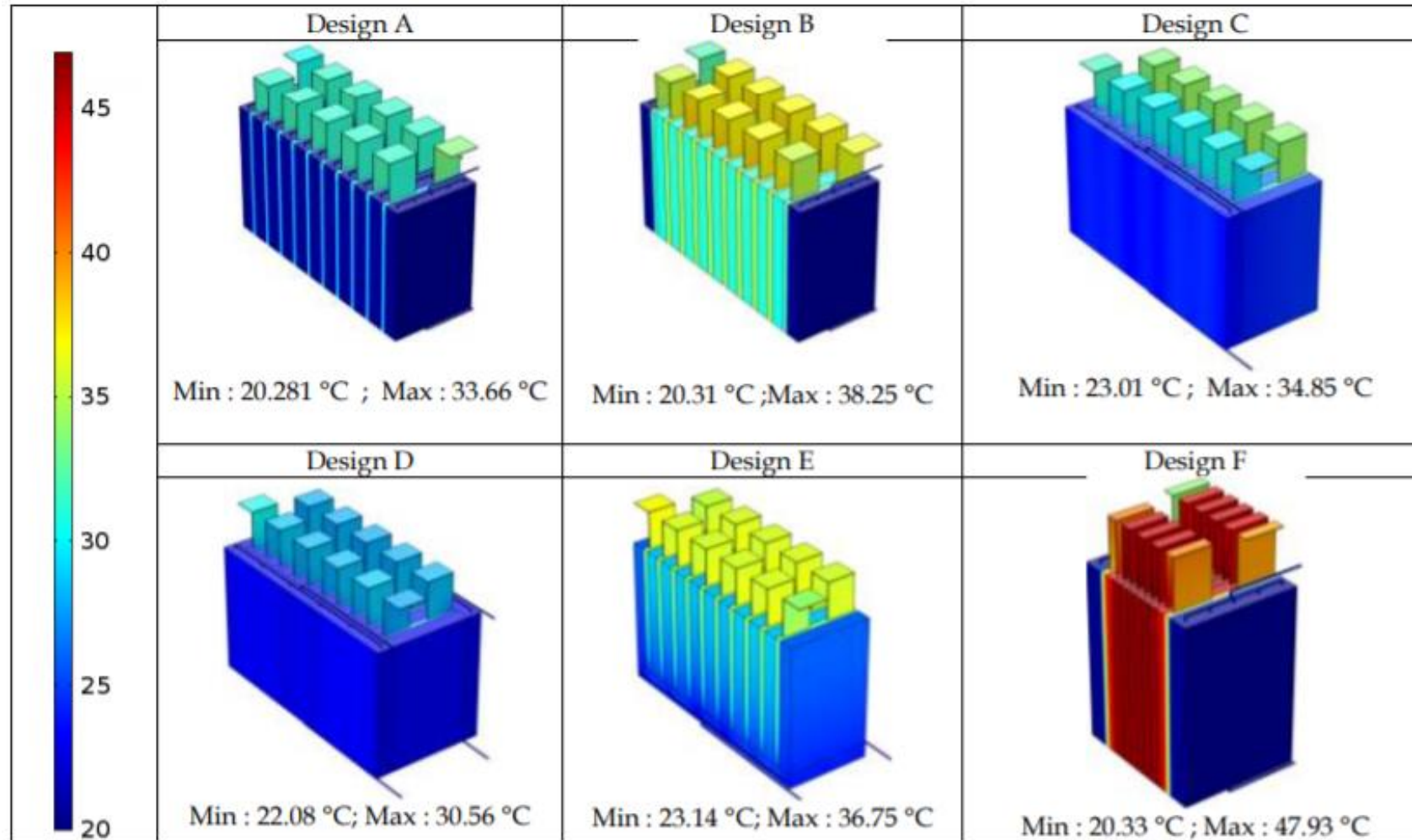
Fonte: Z. Rao and S. Wang, “A review of power battery thermal energy management”. Renewable and Sustainable Energy Reviews. 2011.

Comparação – diferentes conceitos



Fonte: Ahmadou Samba. "Battery Electrical Vehicles-Analysis of Thermal Modelling and Thermal Management". Ph.D. Thesis. Université de caen Basse Normandie. 2015.

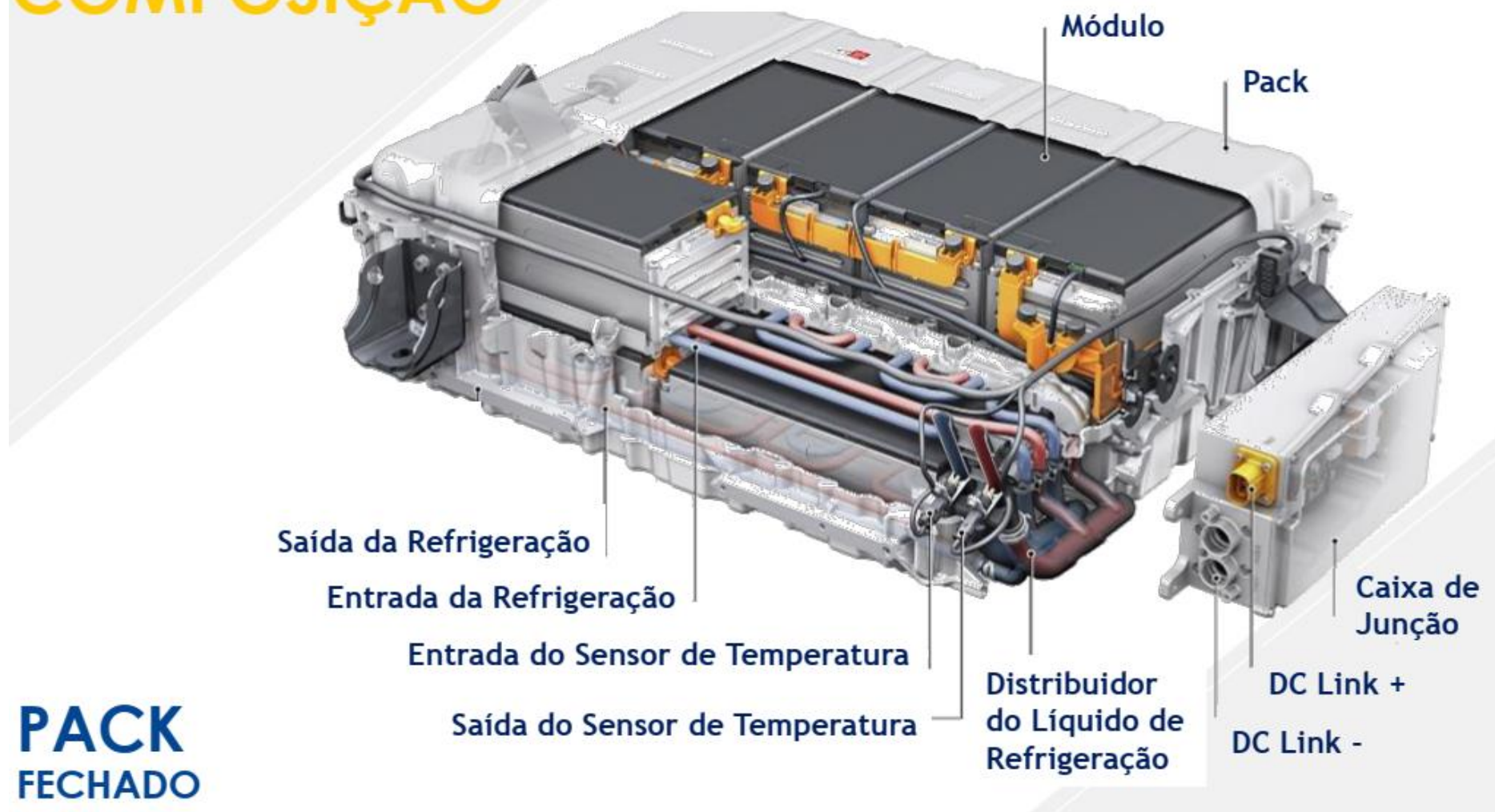
Comparação – diferentes conceitos



Fonte: Ahmadou Samba. “Battery Electrical Vehicles-Analysis of Thermal Modelling and Thermal Management”. Ph.D. Thesis. Université de caen Basse Normandie. 2015.

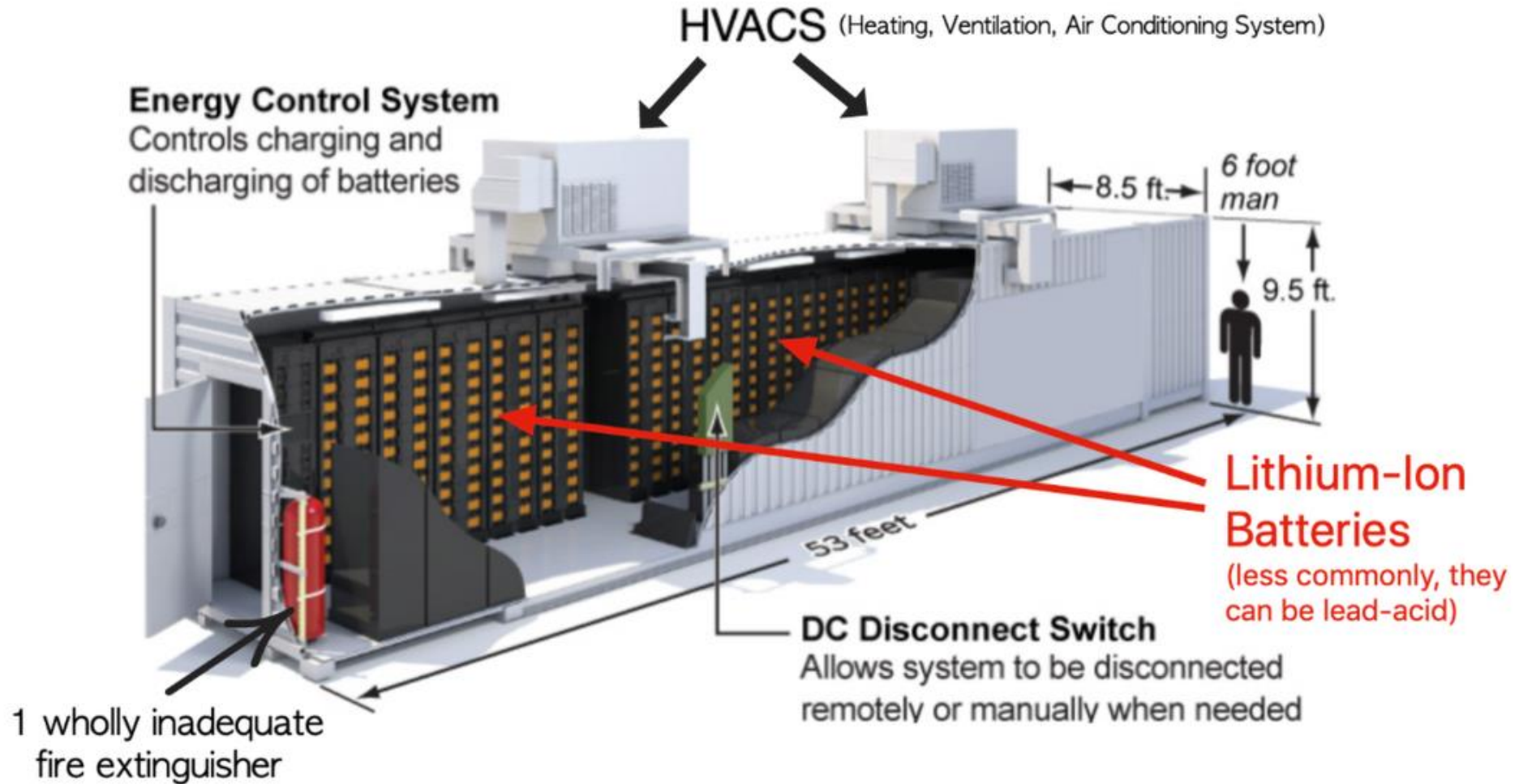
Exemplo - Sistema de monitoramento e manejo térmico

COMPOSIÇÃO



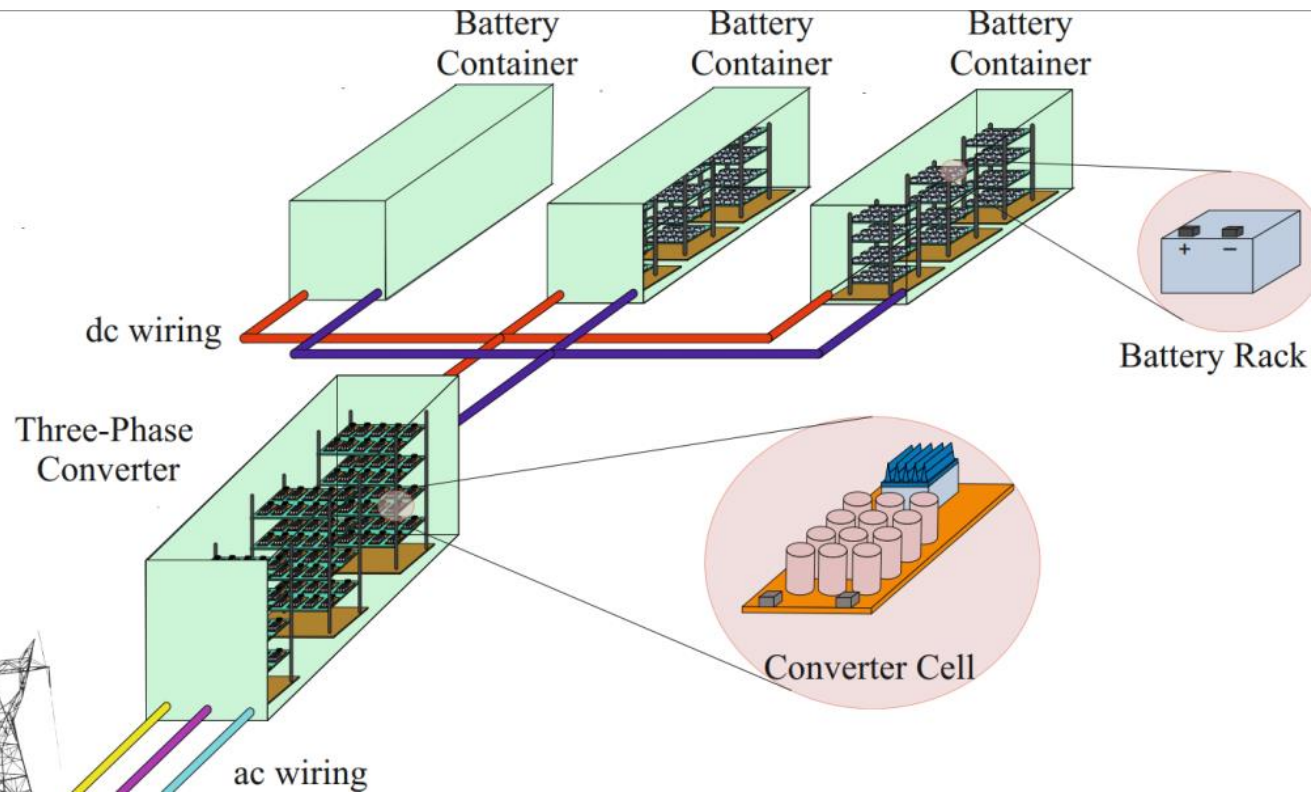
Fonte: Moura

HVACS System



Fonte: Innolia Energy

HVACS System



Fontes:

- [1] S. K. Chaudhary et. Al. "Benchmarking of Modular Multilevel Converter Topologies for ES-STATCOM Realization". Energies. 2020.
- [2] N. Kawakami et. Al. "Development of a 500-kW Modular Multilevel Cascade Converter for Battery Energy Storage Systems". IEEE Transactions on Industry Applications. 2014.

Obrigado pela Atenção



Bons estudos!



Dúvidas: afcupertino@ieee.org



www.gesep.ufv.br



@GESEP



@gesep_vicosa



Gesep



Pesquise por:
“GESEP UFV”



EStimate - Sistemas
Fotovoltaicos



Pesquise por:
“EStimate”