Overview/Scope

Cranfield has two aims:

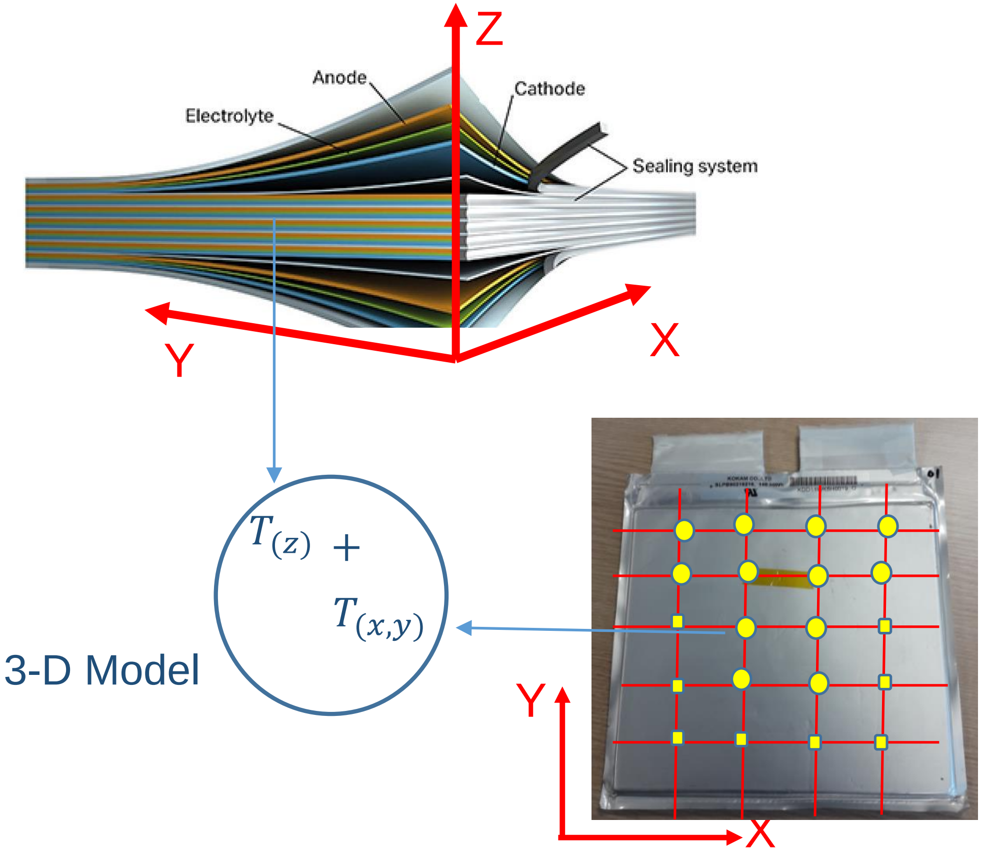
- Develop an internal temperature estimator that can be embedded in the ICP.
- Help ‘prove’ the benefits of the ICP by quantifying improvements in modelling and state estimation accuracy.

Recap: thermal modelling, temperature prediction and thermal controllability

1-D modelling and the calibration into ICP software and firmware	• Galerkin Method (*GM*) • GM using FDM (*Open-Loop*) • A closed-loop control system using FEM-based GM and state observer	**Progress:** • ICP deliverable: 1-D model with state observation and feedback control. • Next step for 1-D model: Model verification and its calibration into software and firmware.
2-D / 3-D modelling, and the innovative methodology	• GM, FDM, and FEM • Novel FD-FEM for thermal modelling in both horizontal and vertical directions • Consider thermal effects from the perspective of electrochemical reactions, materials and structure reformulation.	**Reasons:** (1) Different properties in size and thermal conductivities horizontally and vertically; (2) with different level of meshing, FEM and FDM complement with accuracy and calculation speed respectively; (3) thermal nonlinearities introduced by materials, electrochemical reactions, and structure changes.
Thermal Controllability and a strong promotion	• To replace CFD MSMD module for battery cell with essential prediction and stronger controllability. • Aims on one Nature Scientific Report and one Nature Energy article.	**Expected results:** Significant application for controllable thermal management for ICP cells; A systematic research on macro and micro thermal modelling.

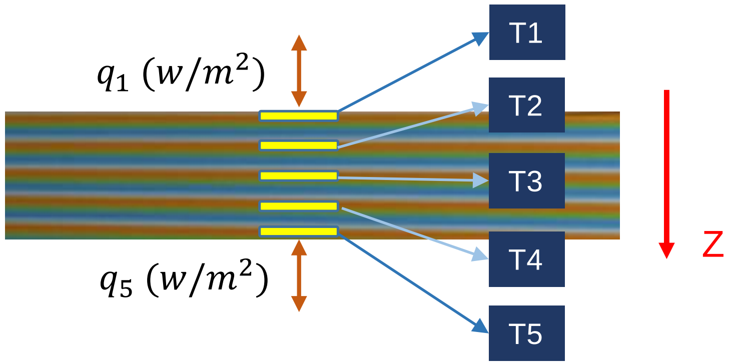
Recap: thermal modelling, temperature prediction and thermal controllability

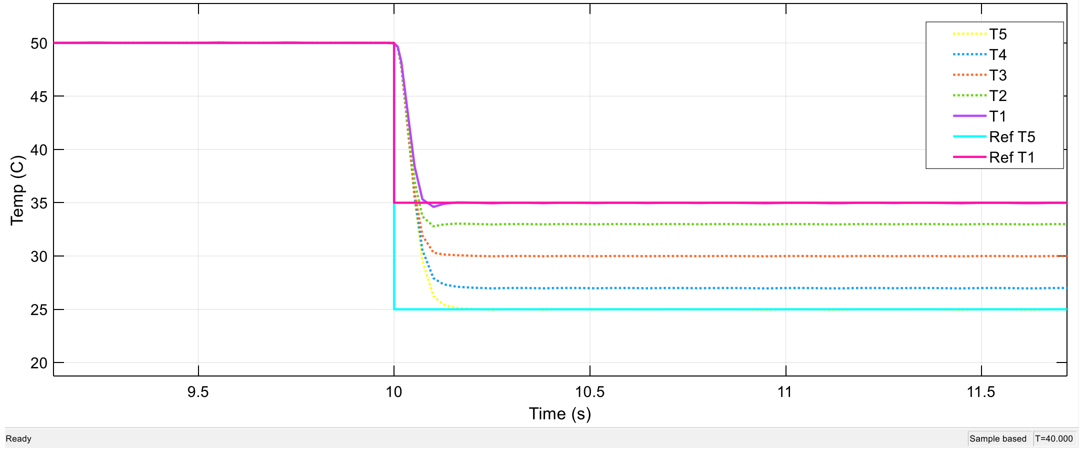
Help to understand the previous page



- Narrow size along *Z* direction, with varying thermal conductivities between layers and higher requirement of meshing accuracy; **[FEM adopted]**
- Wide size along *X or Y* direction, with lower requirement of meshing accuracy; **[FDM adopted]**
- **Compromise** between FEM and FEM, to reach faster calculation.
- Consider factors like materials, electrochemical reactions, and structure / mechanical changes.

Work finished in January 2020: 1-D modelling with GM & FEM






```matlab
%% Original system
 A = [-276.6036  350.8143  -94.4500   26.9857   -6.7464 ;
  175.4071 -323.8286  188.9000  -53.9714   13.4929 ;
  -47.2250  188.9000 -283.3500  188.9000  -47.2250 ;
   13.4929  -53.9714  188.9000 -323.8286  175.4071 ;
   -6.7464   26.9857  -94.4500  350.8143 -276.6036 ];

B = [-0.00001674 0; -0.00001674 -0.00001674; -0.00001674 -0.00001674;
    -0.00001674 -0.00001674;0 -0.00001674];

C = [1 0 0 0 0; 0 0 0 0 1];
Cforall = [1 0 0 0 0; 0 1 0 0 0; 0 0 1 0 0; 0 0 0 1 0; 0 0 0 0 1];

%% Extended system for tracking control of T1 and T5
 Aa = [-276.6036  350.8143  -94.4500   26.9857   -6.7464 0 0;
  175.4071 -323.8286  188.9000  -53.9714   13.4929 0 0;
  -47.2250  188.9000 -283.3500  188.9000  -47.2250 0 0;
   13.4929  -53.9714  188.9000 -323.8286  175.4071 0 0;
   -6.7464   26.9857  -94.4500  350.8143 -276.6036 0 0;
   1 0 0 0 0 0 0;
   0 0 0 0 1 0 0];
```

```matlab
%% There are two reference inputs - the reference signals T1 and T5.
%% Two control inputs (boundary flux) q1 and q5
%%
p1 = -40+40i;
p2 = -40-40i;
p3 = -40;
p4 = -50+50i;
p5 = -50-50i;
p6 = -60;
p7 = -100;
Ka = place(Aa,Ba,[p1,p2,p3,p4,p5,p6,p7]);% Pole placement (using state feedback) for
%extended system with tracking error equations for T1 and T5, computes a
%state-feedback matrix.
Kc=Ka(:,1:5);
Ki=Ka(:,6:7);  %% Control gain for two control inputs - heat flux q1 and q5.
% t = 0:0.01:0.5;
sys_ex = ss(Aa-Ba*Ka,Br,Ca,Da);
% step(sys_ex,t);
opt = stepDataOptions('StepAmplitude',25);
step(sys_ex,opt);

%% State observation based on the above Tracking Control
%
L = place(A',C',[p1*10, p2*10, p3*10, p4*10, p5*10]);
```

Data generation

Technical paper:

- THT follows the Experimental program proposed by Imperial College on the ICP.

    Pulse discharge in progress

    Temperature set point to be done next

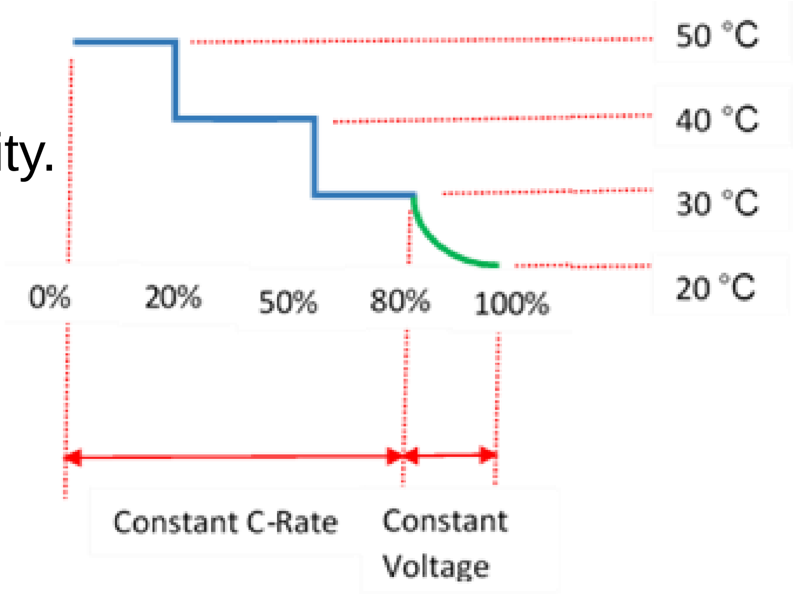
- Experimental program proposed by Cranfield University.

    Pulse discharge with back to back cells

    Temperature set point with back to back cells

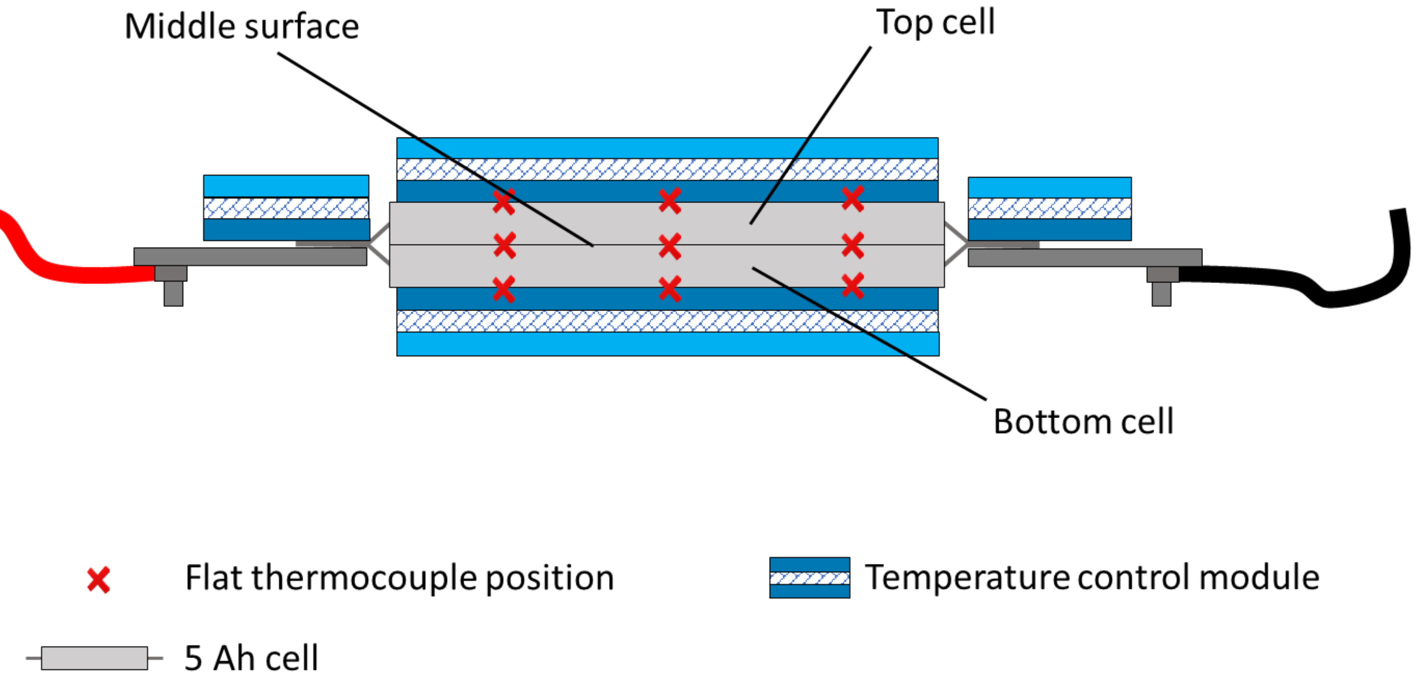
    Charge test protocol

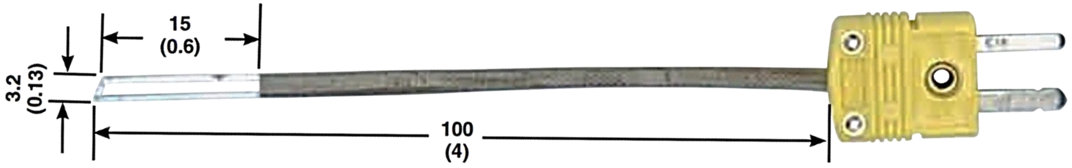
Charge test protocol (different C rates)



Testing

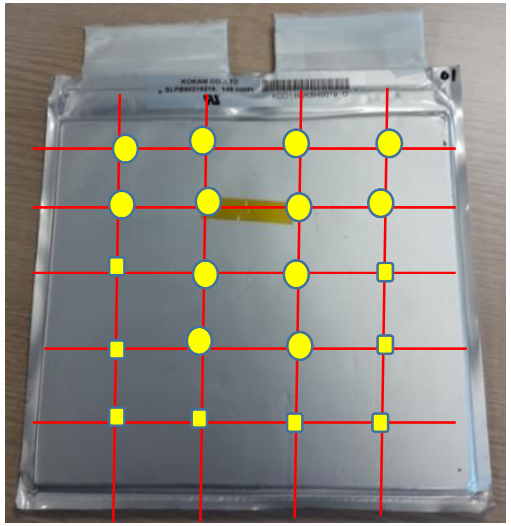
Cranfield: Model calibration – Experimental setup



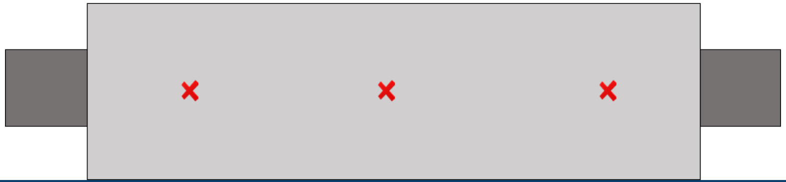


Thickness : 0.05 mm

Ideally :
20 thermocouples per surface



Simplify

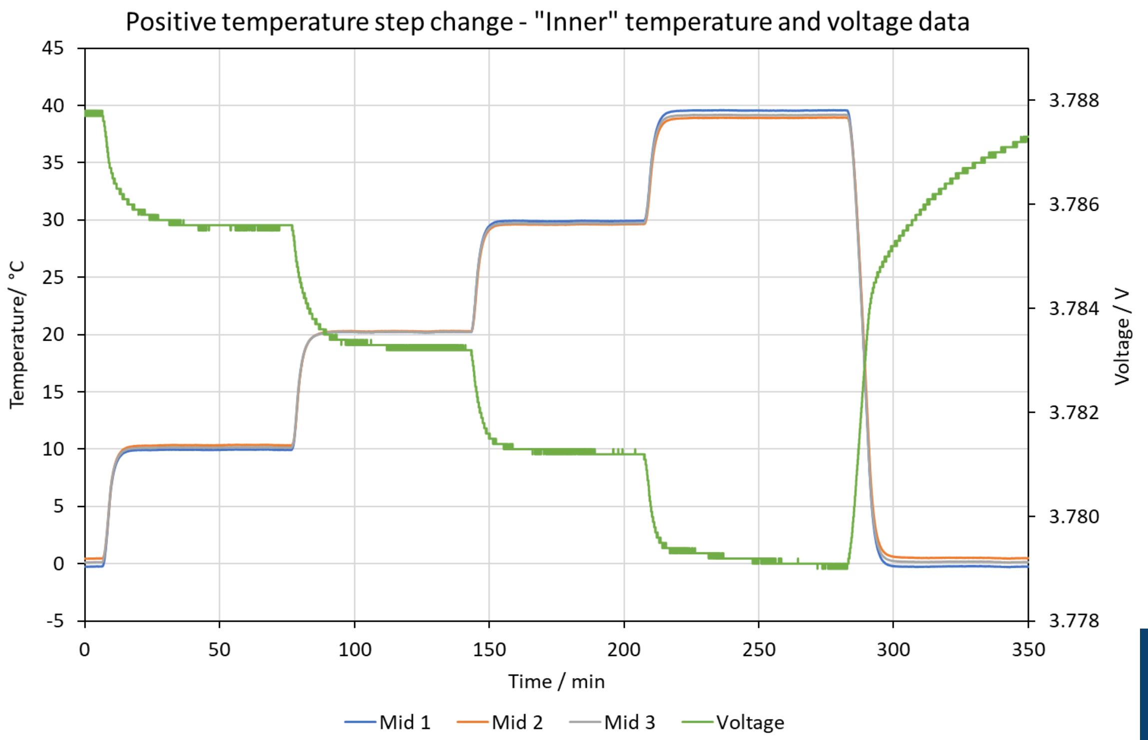


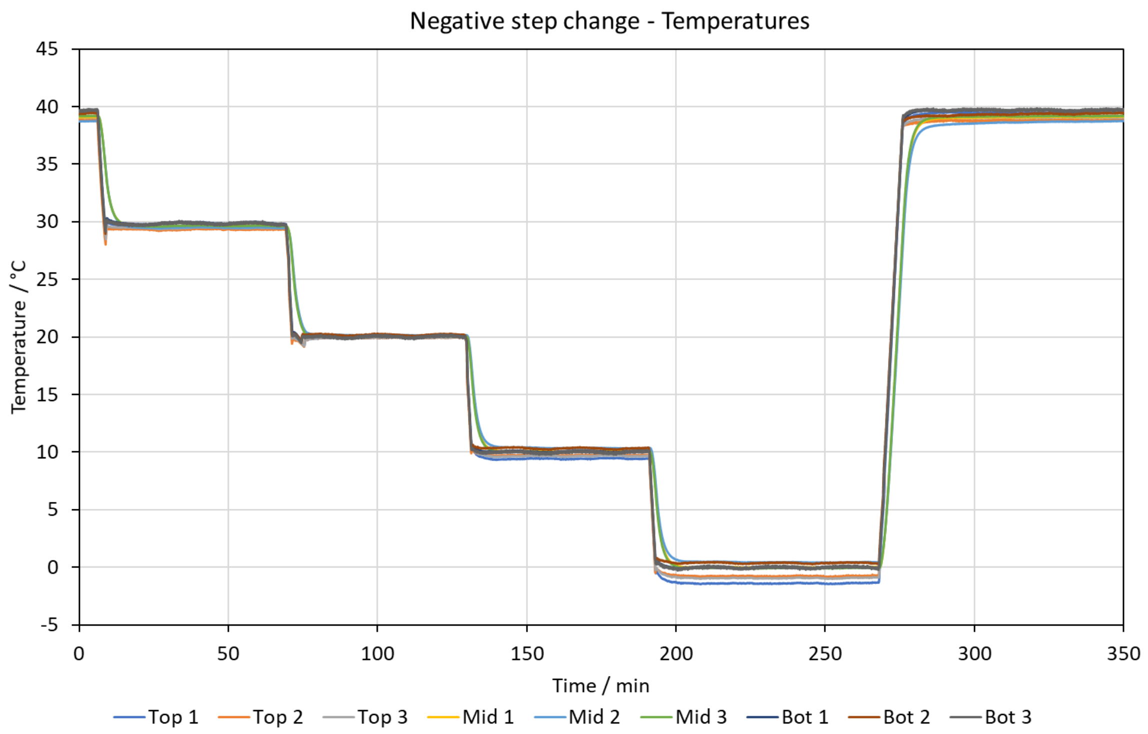
3 thermocouples per surface

Testing

Cranfield: Model calibration – Temperature step change

Positive step change		Negative step change	
Start temp. (°C)	End temp. (°C)	Start temp. (°C)	End temp. (°C)
0	10	40	30
10	20	30	20
20	30	20	10
30	40	10	0
40	0	0	40

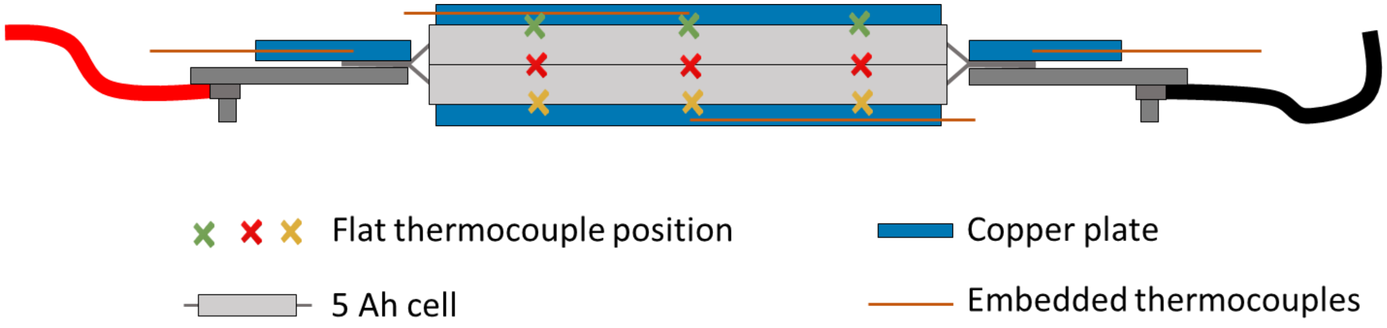




Testing

Cranfield: Model calibration – Flat thermocouples offset

- Temperature offset between TCs
- Offset dependent of the temperature
- Larger at 0 °C and 40 °C (up to



Pulse discharge 20 °C   100 – 50 %