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Simulation and testing of a latent heat thermal energy storage unit with metallic phase change materials

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Fakulteit Ingenieurswese
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Faculty of Engineering

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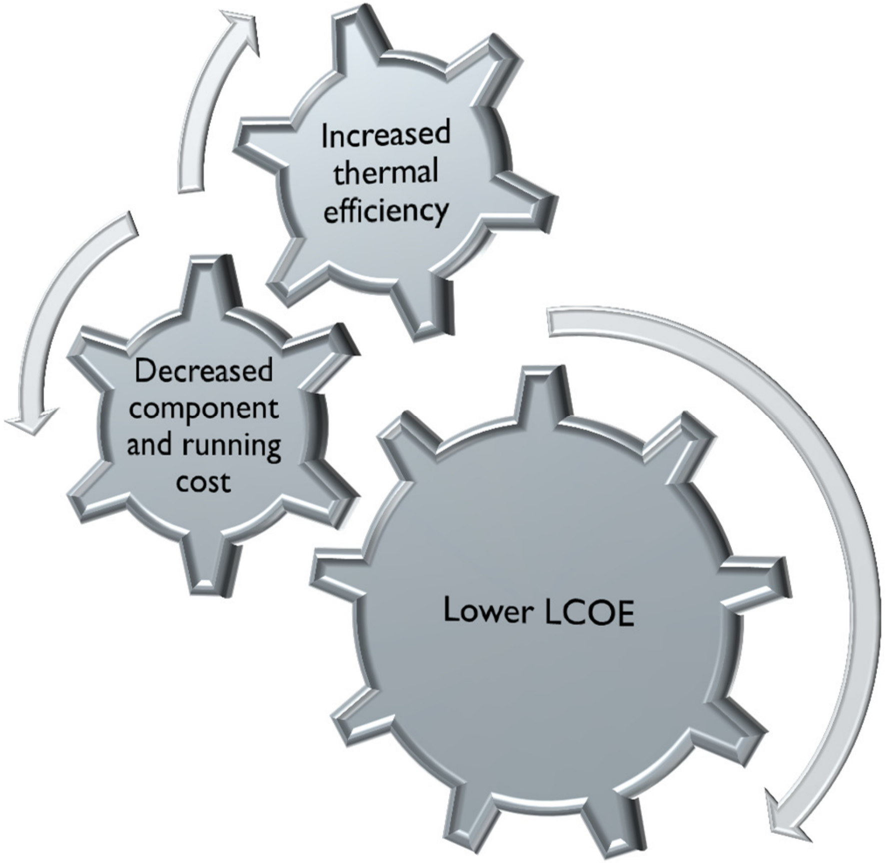
Aims in CSP



Increased thermal efficiency
Decreased component and running cost
Lower LCOE

Cost breakdown of a CSP plant (DOE case study)

Cost breakdown of LCOE (All costs)		
Heliostat cost	22.1	%
Indirect costs	20.8	%
Operations and maintenance	12.1	%
Power plant cost	12.1	%
Receiver cost	10.1	%
Tax	8.1	%
Storage cost	7.4	%
Balance of plant cost	4.0	%
Site cost	2.0	%
Tower cost	1.3	%

DOE – CSP calculation at 15 US$ cents/kWh

41% of the costs are due to indirect costs and is site specific

Still, heliostats relates to 37.5% of the total hardware cost

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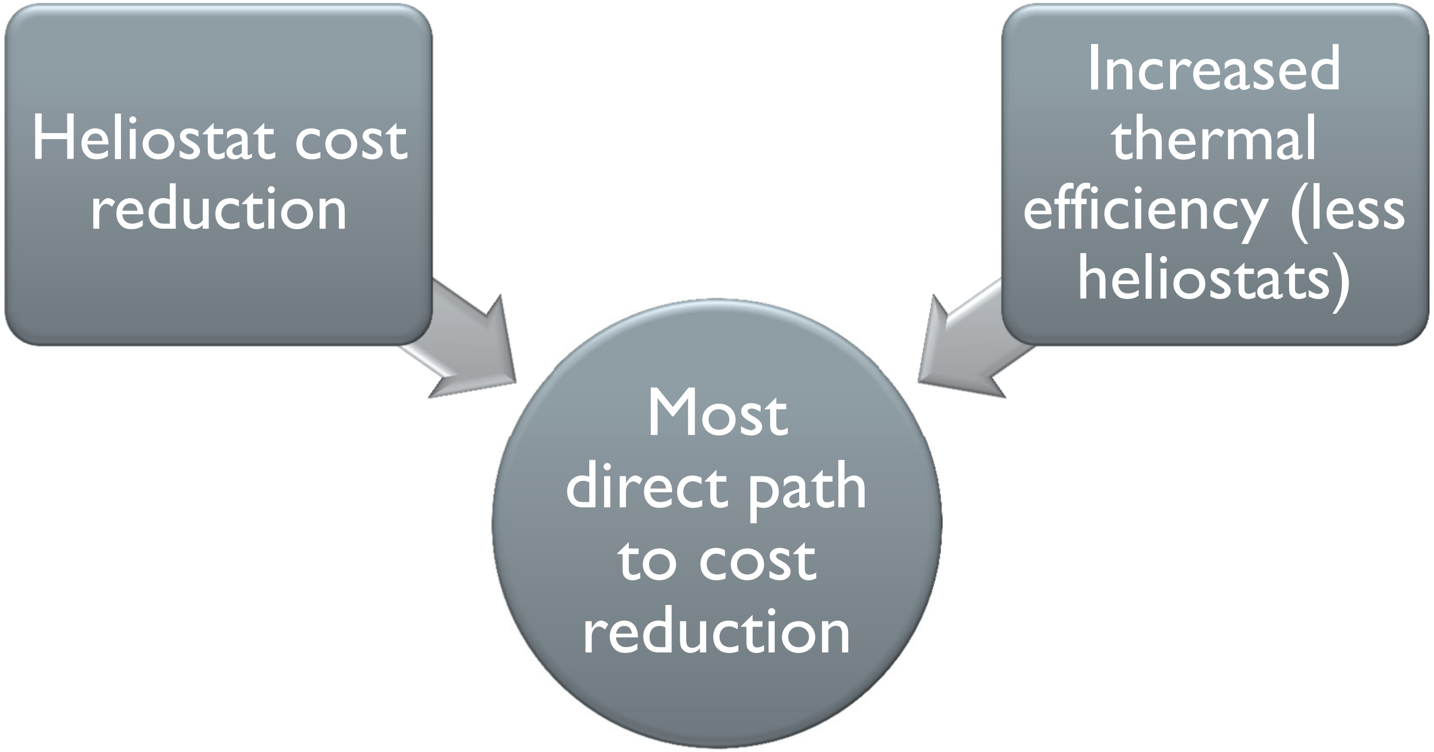
Most efficient method of cost reduction

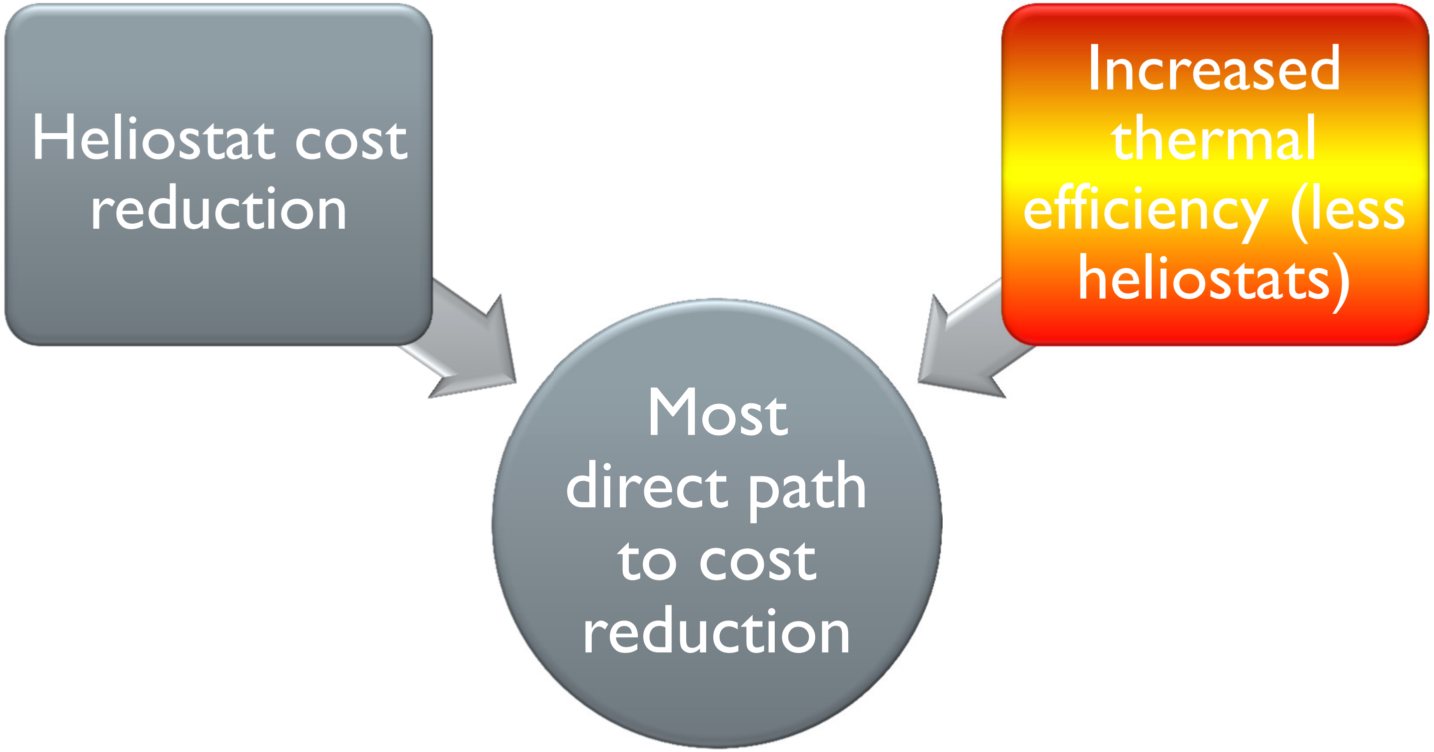


Heliostat cost reduction

Increased thermal efficiency (less heliostats)

Most direct path to cost reduction

Most efficient method of cost reduction



Heliostat cost reduction

Increased thermal efficiency (less heliostats)

Most direct path to cost reduction

Increased thermal efficiency of power block

Technology	**Source temperature**	**Thermal efficiency**
Subcritical steam	540°C	~36%-40%
Supercritical / Ultra supercritical steam	600°C	~48%-52%
CO_2 Brayton cycles (S-CO_2)	550°C	~45%

Higher source temperatures are required.

- Consider a 10% increase in thermal efficiency from a usual subcritical steam power block to a ultra supercritical steam power block:
  - 26.3% savings in thermal input from the heliostats.
  - 26.3% less heliostats
  - And a 5.8% reduction in LCOE, and a 9.8% reduction in plant cost based on heliostats alone.

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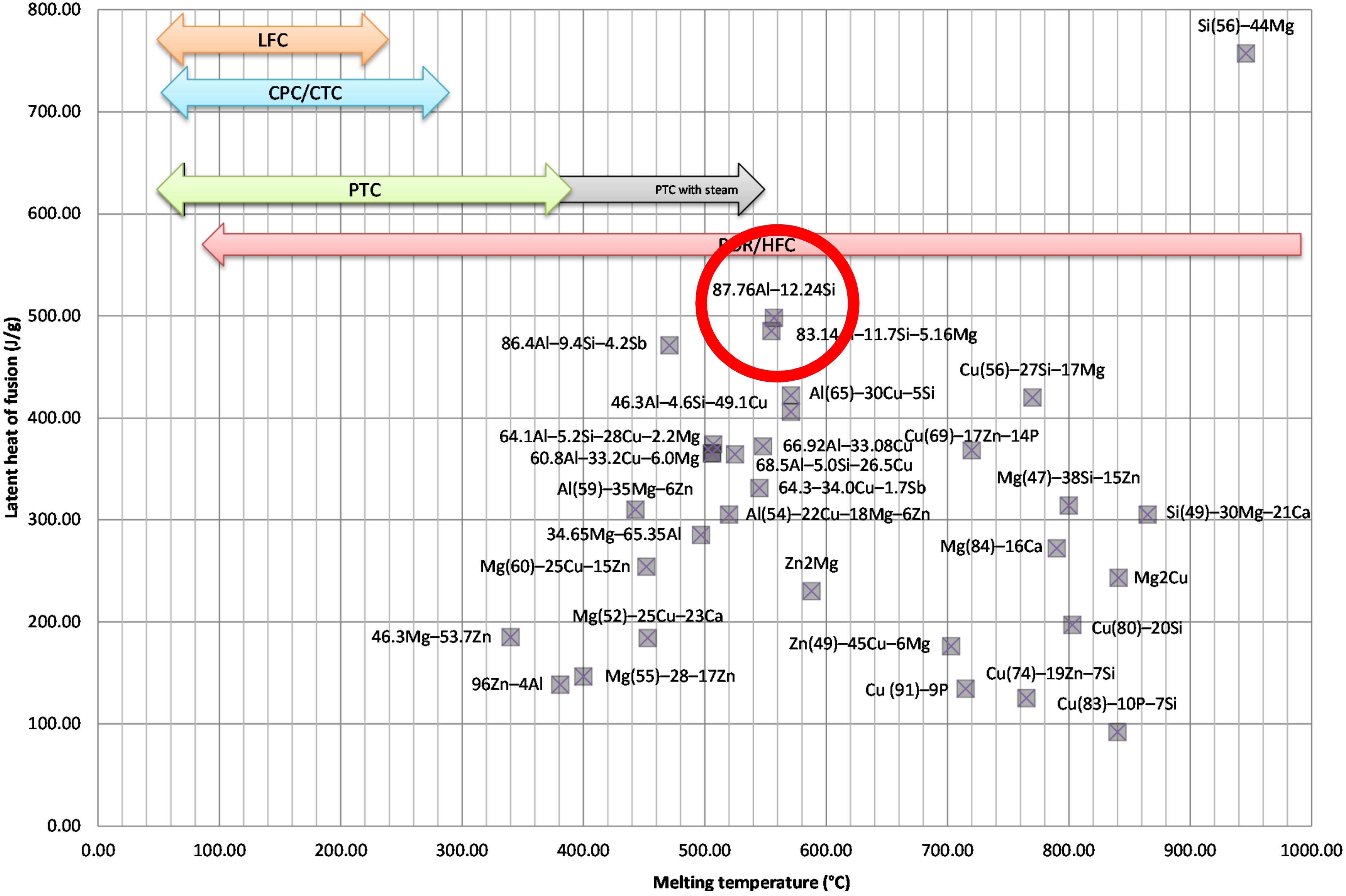
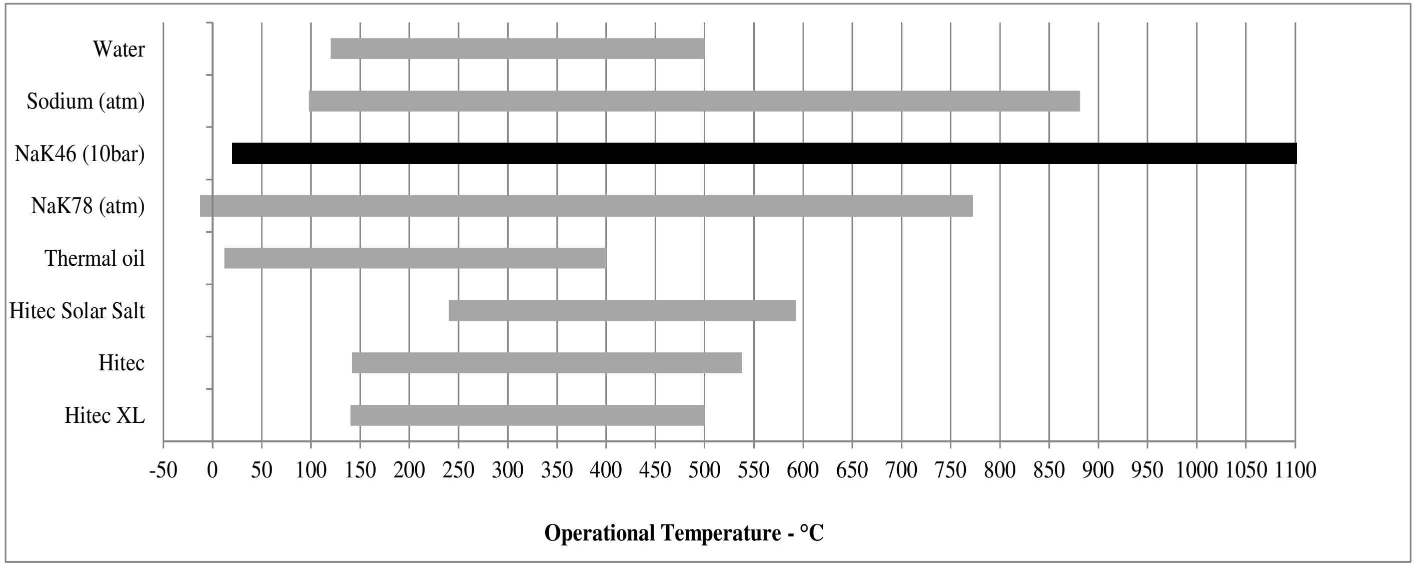
Metallic PCM – Material selection for research

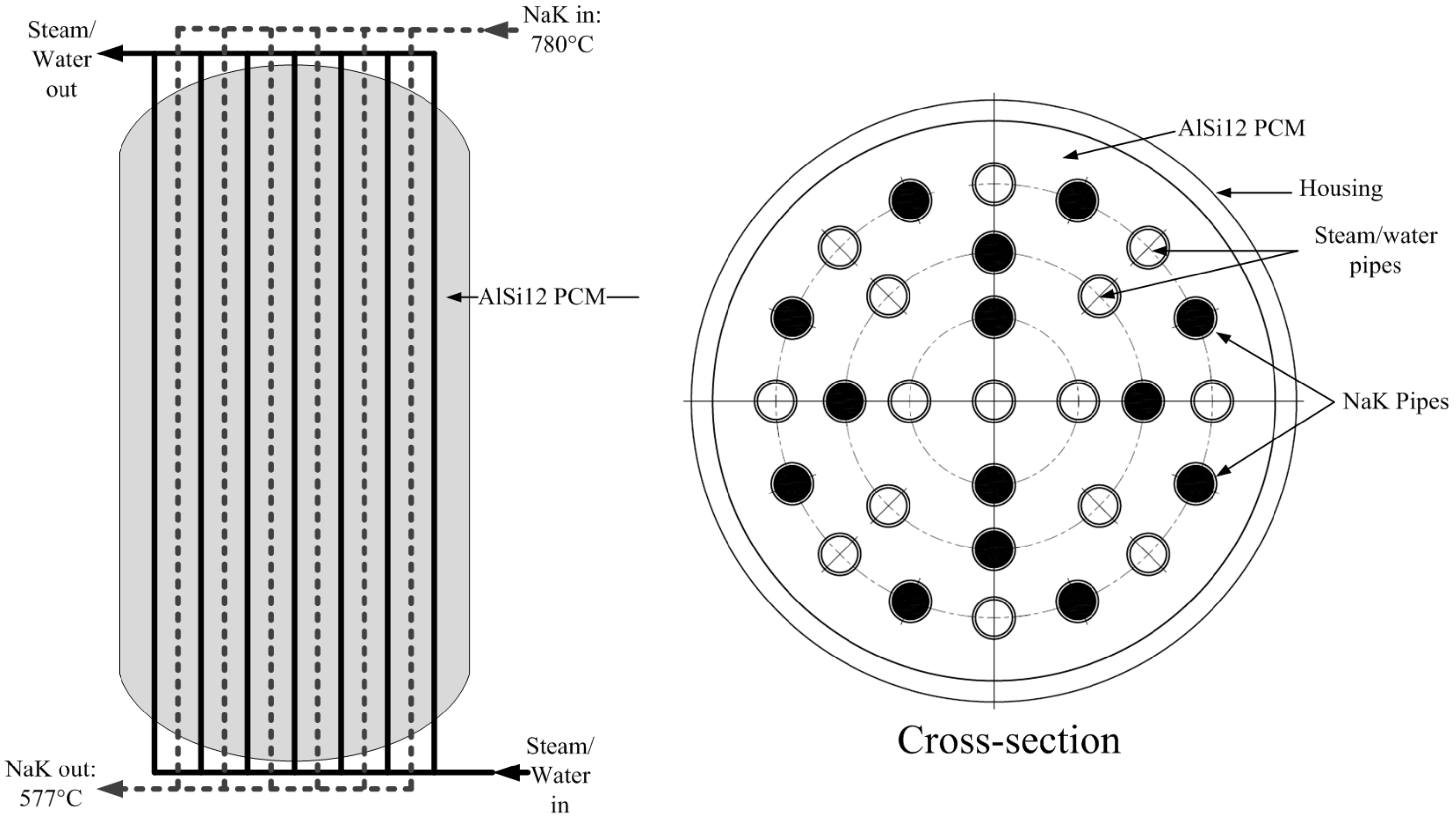


Heat transfer fluids

- Of all the HTFs, NaK is best suited for attaining higher receiver temperatures
- The low melting point means increased plant reliability, and lower operational cost.

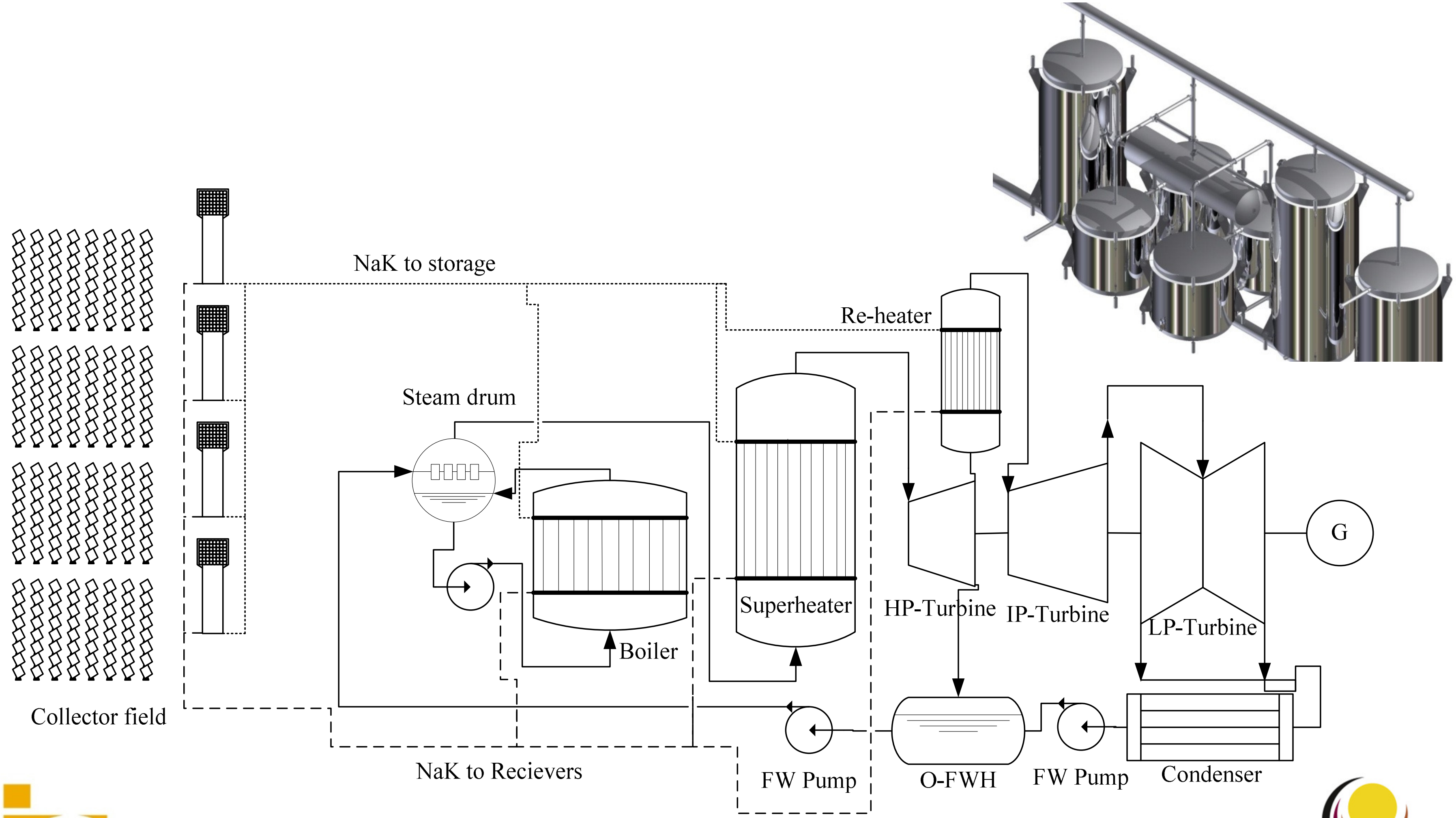


Introduction – Combined storage and steam generator concept



Cross-section

Potential concepts: Metallic phase change material – Direct steam generation from storage



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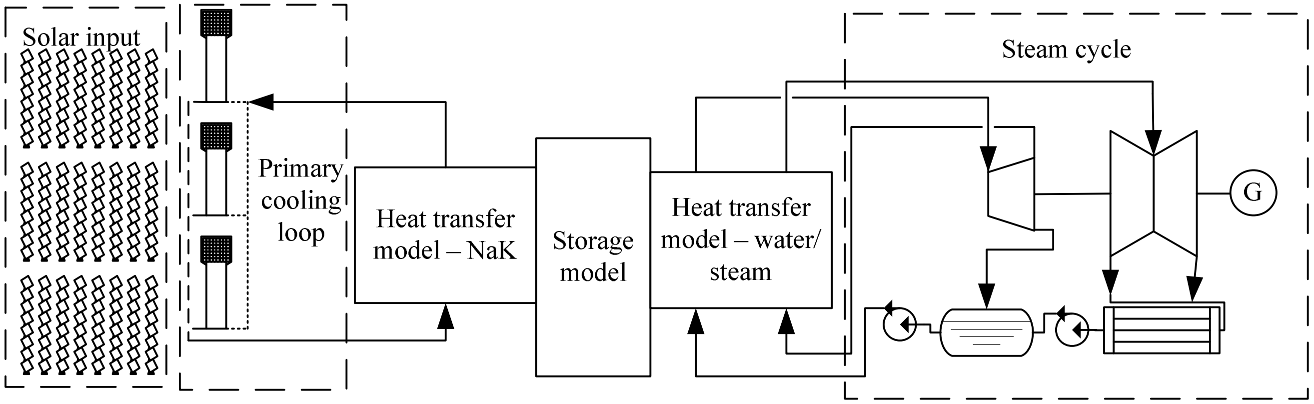
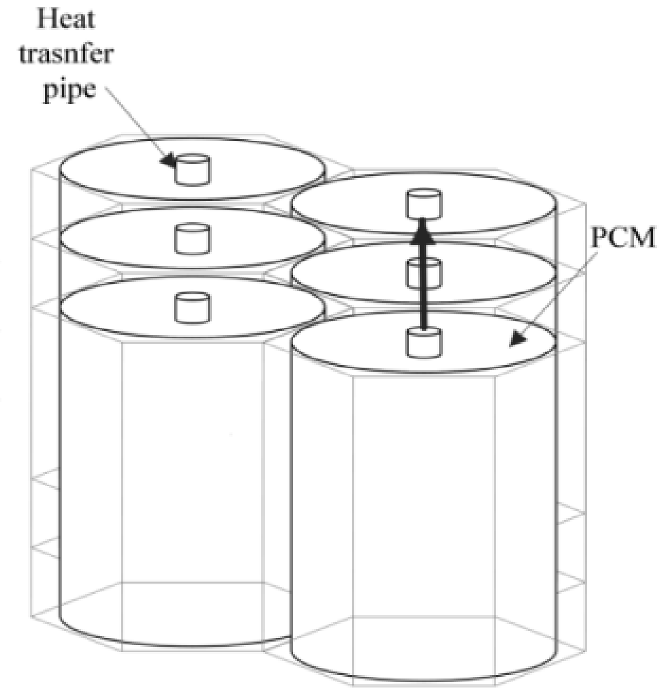
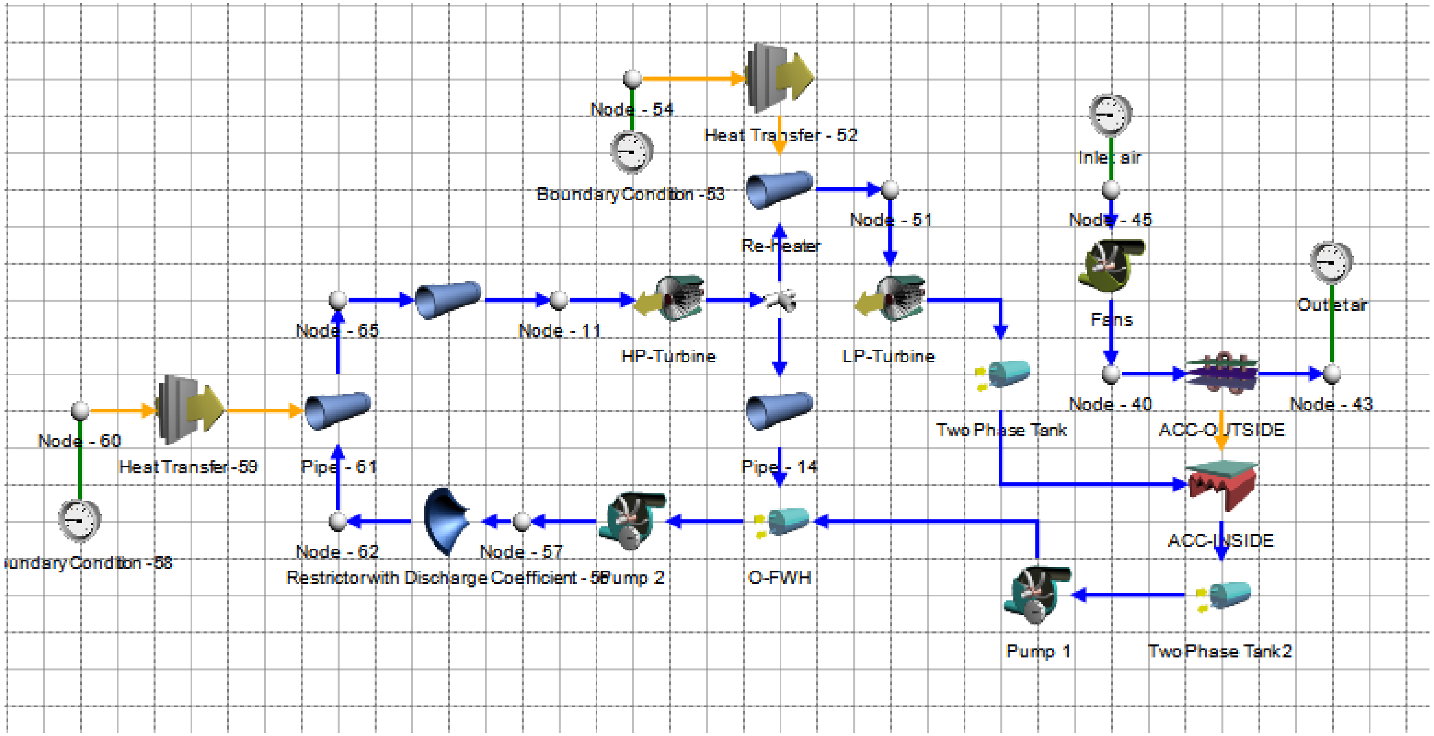
Simulation - Overview



Discretization of heat storage unit

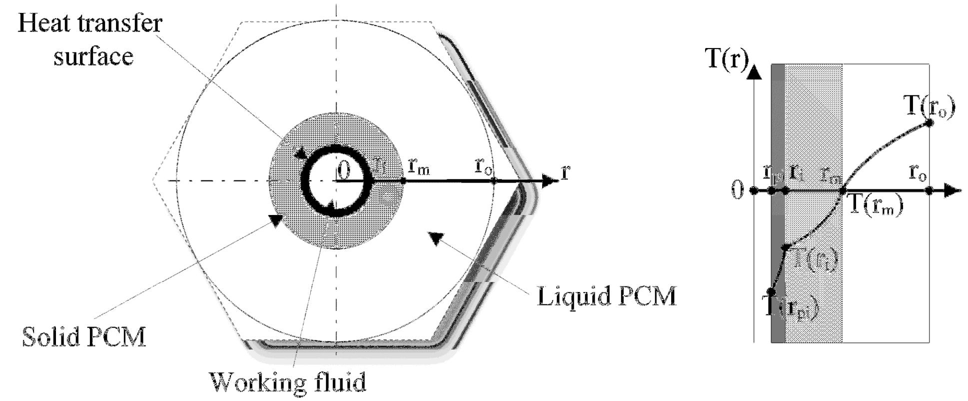


Simulation - Flownex

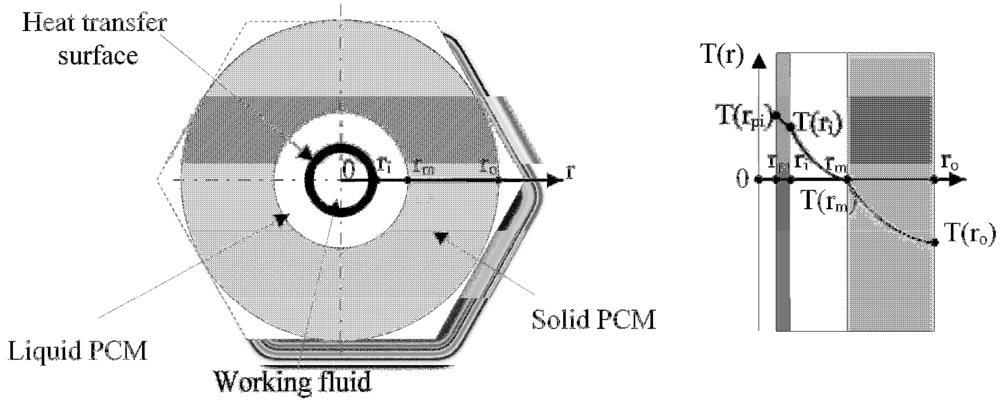


Transient state thermal model

Discharging



Charging



Mathematical formulation

Governing equation: One dimensional heat conduction equation

$$\frac{\delta T}{\delta t} = \alpha \frac{\delta^2 T}{\delta r^2} + \frac{\alpha}{r}\frac{\delta T}{\delta r}$$

Boundary conditions:

$$-kA\frac{\partial T(r_{pi},t)}{\partial r} = Q_{oil}(\mathrm{t})$$

$$-k_p\frac{\partial T_p(r_{i,}t)}{\partial r} = k_{PCM}\frac{\partial T_{PCM}(r_i,t)}{\partial r} \qquad T_p(r_i) = T_{PCM}(r_i)$$

$$\frac{dr_m(t)}{dt} = \frac{k_s}{\rho H_f}\frac{\partial T_s(r_m(t),t)}{\partial r} - \frac{k_l}{\rho H_f}\frac{\partial T_l(r_m(t),t)}{\partial r} \qquad T_l(r_m) = T_s(r_m)$$

$$-k_p\frac{\partial T_p(r_{o,}t)}{\partial r} = 0$$

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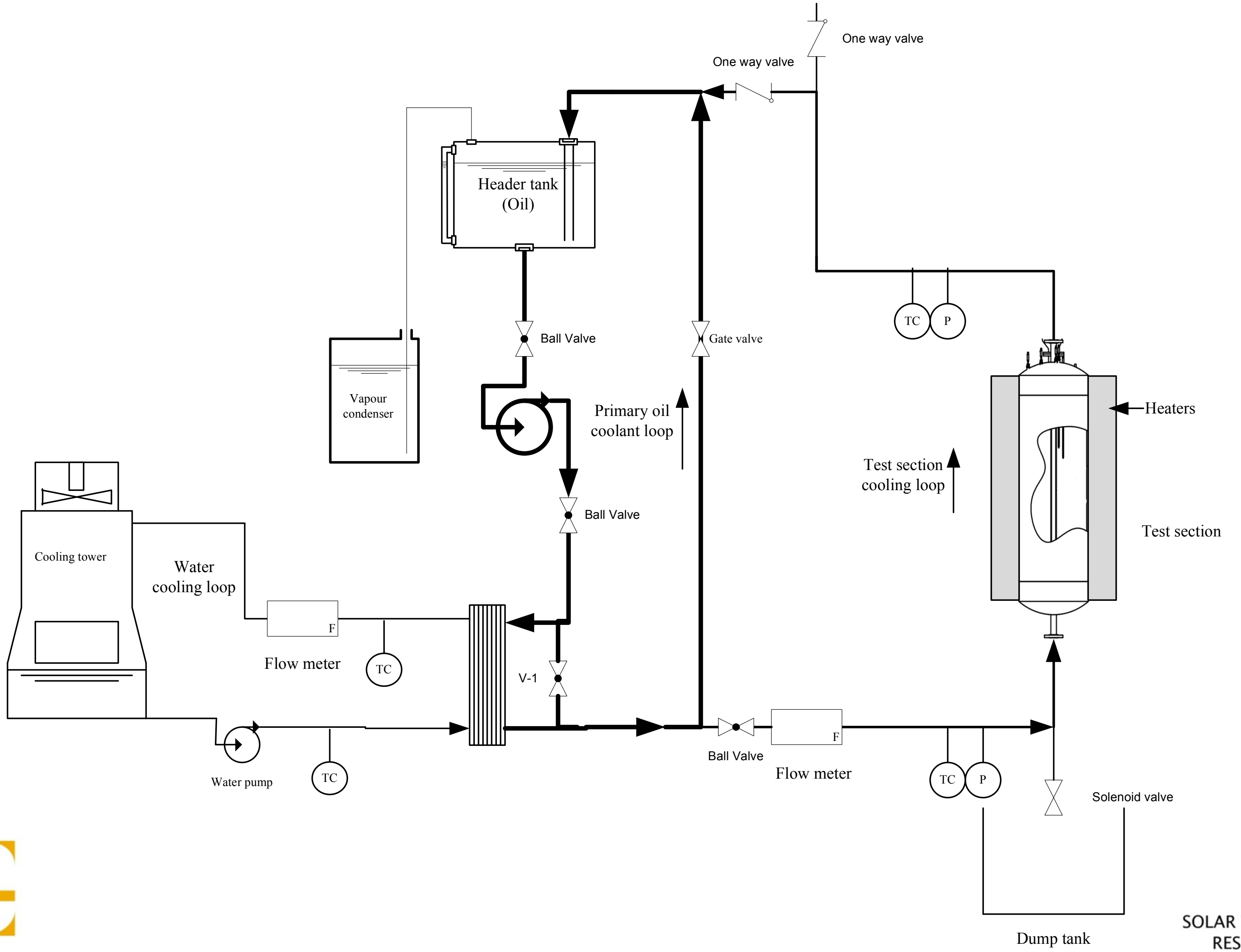
Implementation – Finite difference method

$$\frac{\delta T}{\delta t} = \alpha \frac{\delta^2 T}{\delta r^2} + \frac{\alpha}{r} \frac{\delta T}{\delta r}$$

$$\frac{{T_m}^{p+1} - {T_m}^{p}}{\Delta t} = \alpha \frac{{T_{m+1}}^{p} + {T_{m-1}}^{p} - 2{T_m}^{p}}{\Delta r^2} + \frac{\alpha}{r} \frac{{T_{m+1}}^{p} - {T_{m-1}}^{p}}{2\Delta r}$$

- Boundary conditions had been implemented accordingly
- Moving boundary implemented through a energy balance

Experiment:



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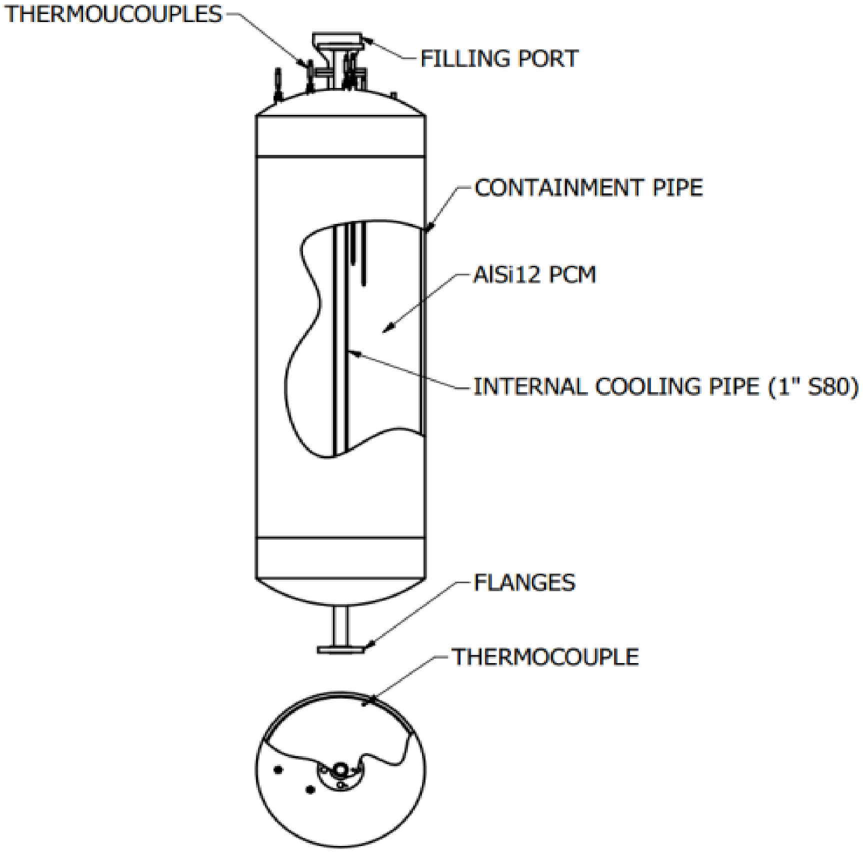
Cylinder geometry		
Outer cylinder		
Inside diameter	398	mm
Outside diameter	408	mm
Heat transfer pipe		
Inside diameter	24.4	mm
Outside diameter	33	mm
Length in contact with AlSi12	1270	mm
Volume of AlSi12	0.1533	m^3
Mass of AlSi12	408	kg
Thermocouple placement from the centre		
Probe 1	30	mm
Probe 2	45	mm
Probe 3	90	mm
Probe 4	135	mm
Probe 5	180	mm



Experiment:

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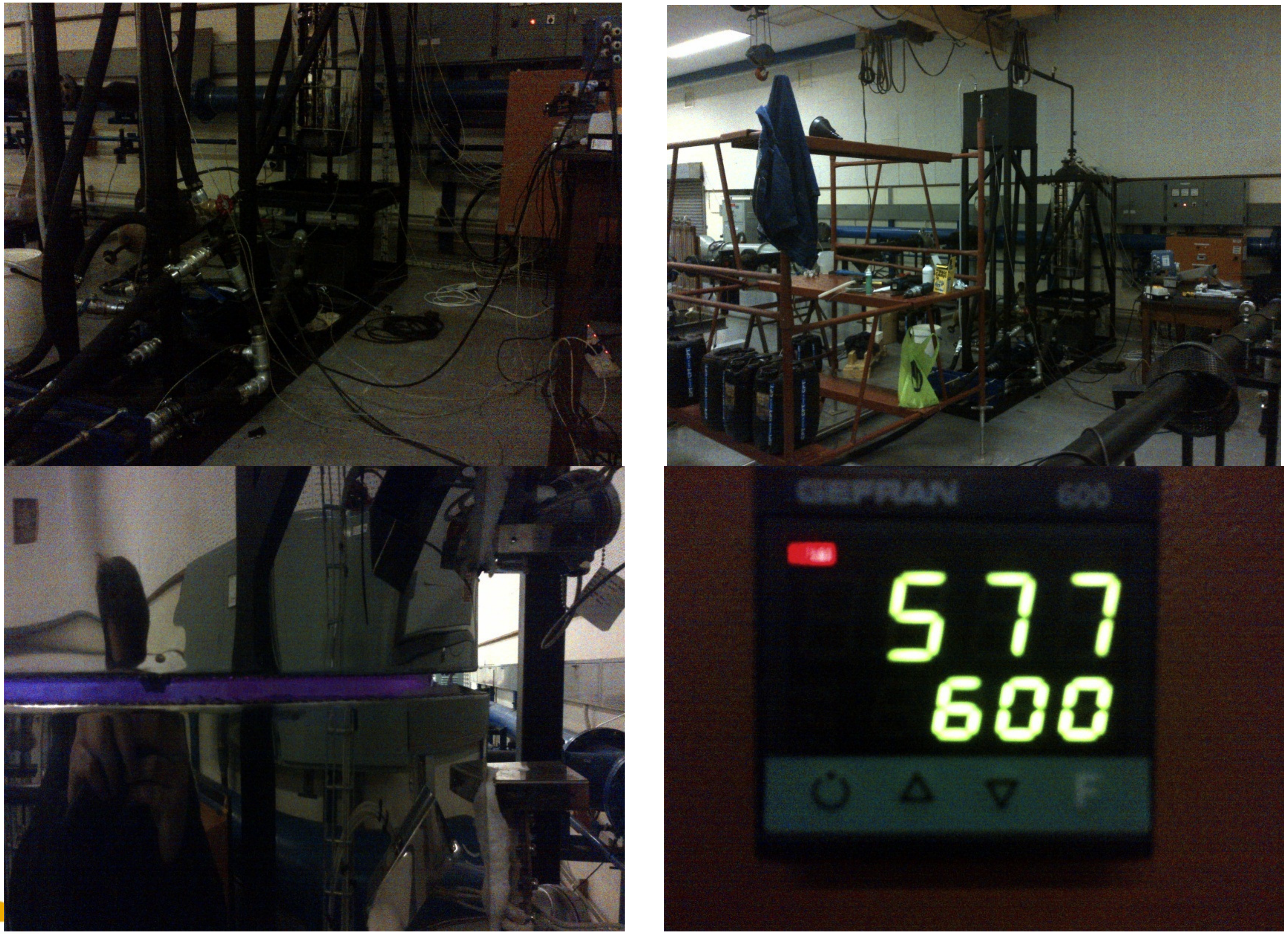

Experiment:

Experiment:

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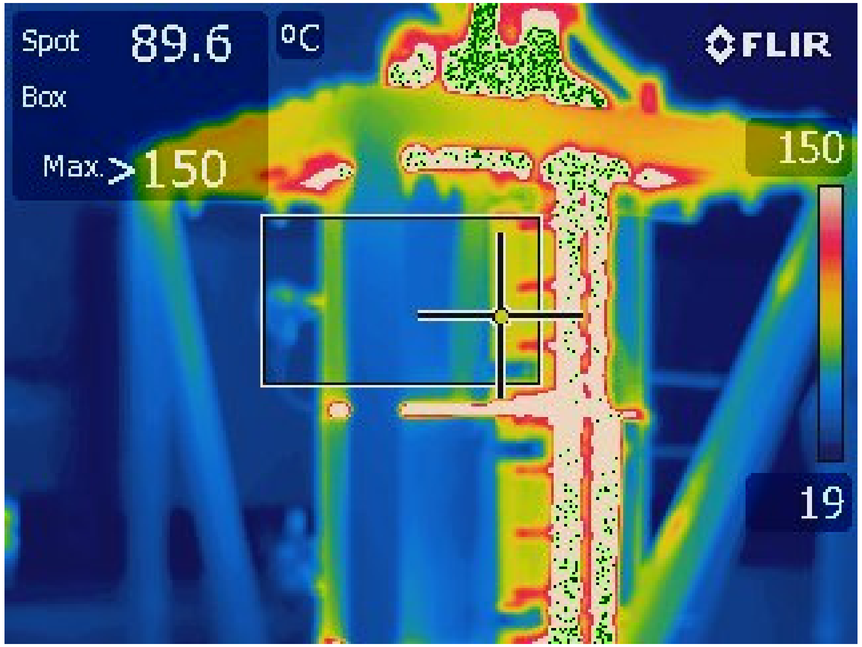
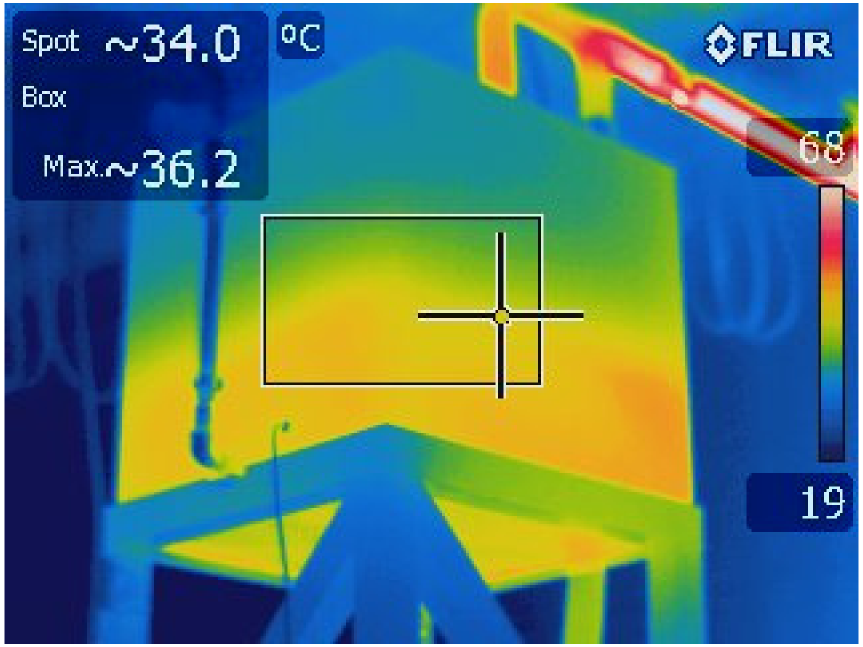
Experiment:

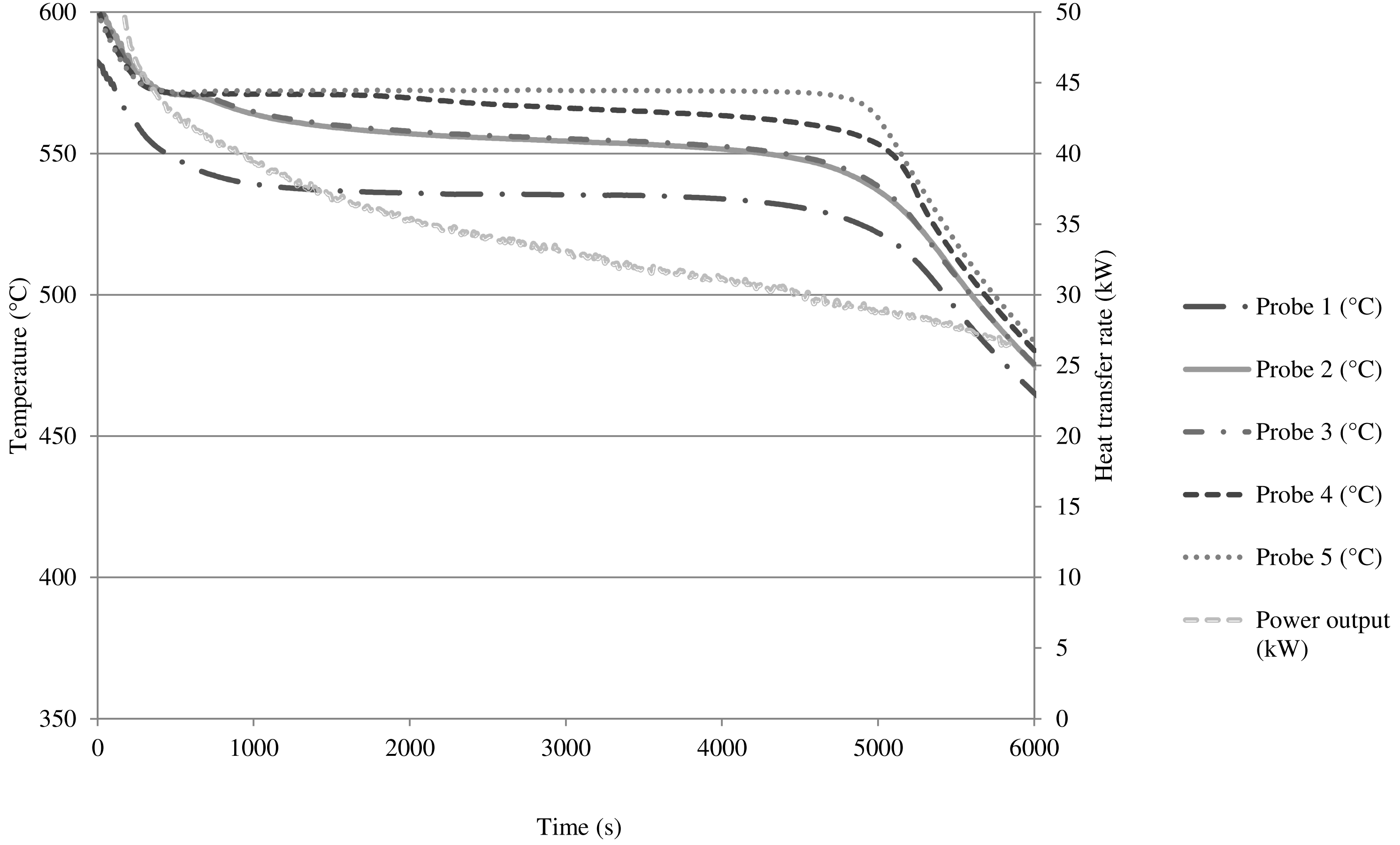

Spot 89.6
°C
Box
Max.>150
FLIR
150
19


Spot ~34.0
°C
Box
Max.~36.2
FLIR
68
19

Thermal properties:

Thermophysical properties of AlSi12			Source
Density	2661	kg/m^3	[5]
Specific heat	0.939	kJ/kg.k	[5]
Heat of fusion	515	kJ/kg	[5] / Measured: DSC
Phase change temperature	577	°C	[5] / Measured: DSC
Thermal conductivity	181	W/m.K	[5]
Thermophysical properties of Mild steel			
Density	7854	kg/m^3	
Specific heat	1.169	kJ/kg.k	
Thermal conductivity	30	W/m.K	
ISO 100 quenching oil			
Density at 60 °C	890	kg/m^3	Measured: Lab
Specific heat at 60 °C	1.950	kJ/kg.K	Measured: MDSC
Kinematic viscosity at 60 °C	20.2	mm^2/s	Measured: ASME1321

Experimental results:



- 78.5 minutes of isothermal discharge at a average of 35kW
- 577°C
- It is clear that the movement of the solidification front do not influence

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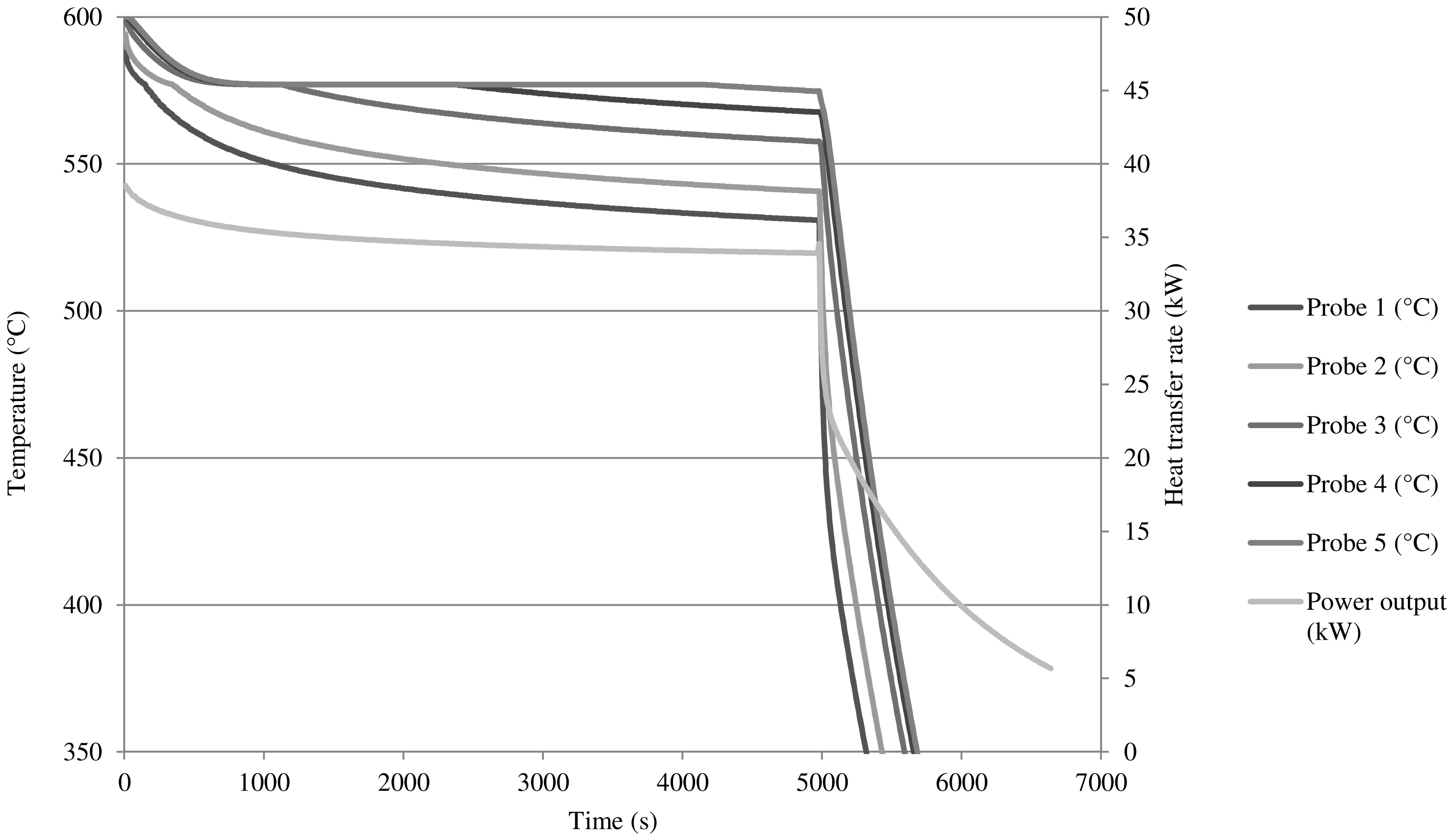
Experimental results:



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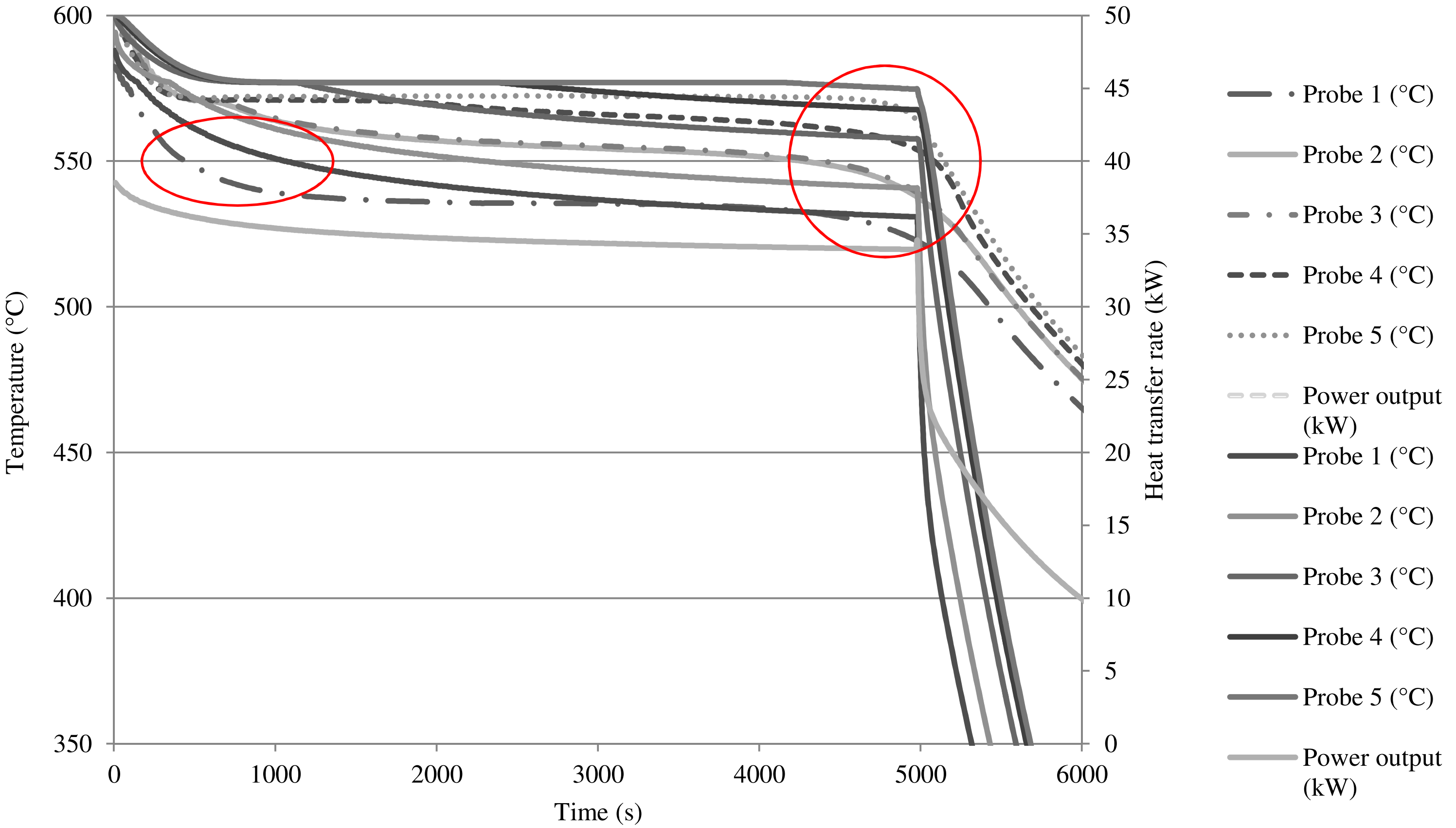
Experimental results:



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Conclusions

- A prototype latent heat thermal energy storage unit has been built and tested.
- Isothermal storage has been achieved
- It is possible to predict the latent heat discharge process, but more work is needed on the sensible cooling model. This will increase the accuracy of the overall model.

Acknowledgments

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