Webinar "Optimized Waste Heat Recovery via Integrated Emerging Thermal Energy Conversion and Storage Technologies" – 28th February 2025

zhenit

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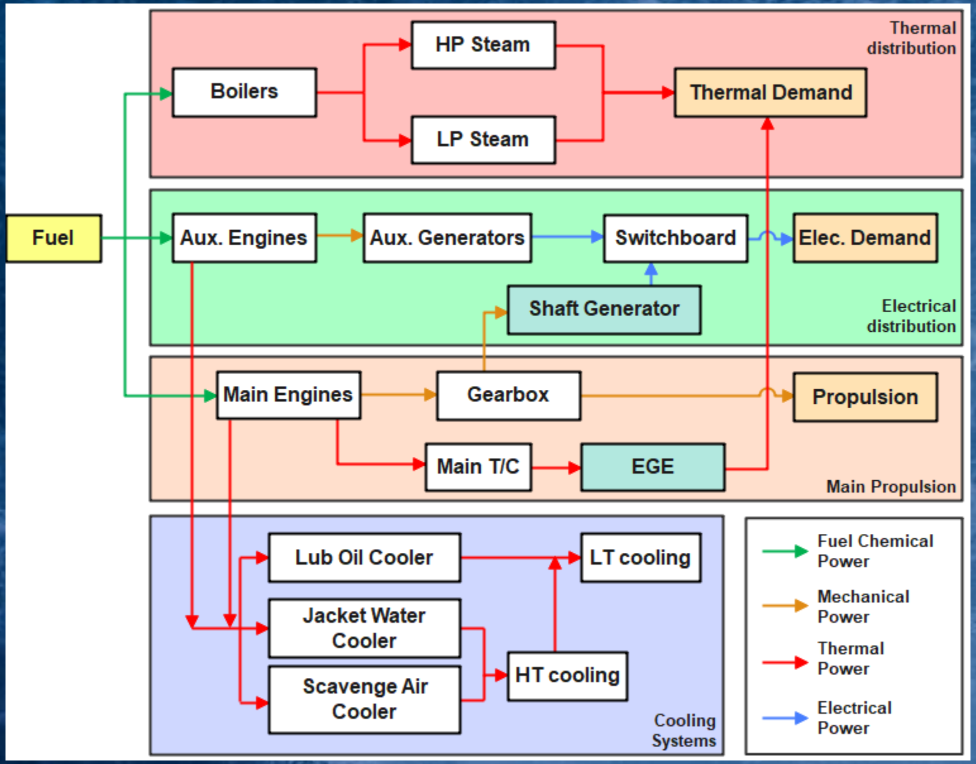
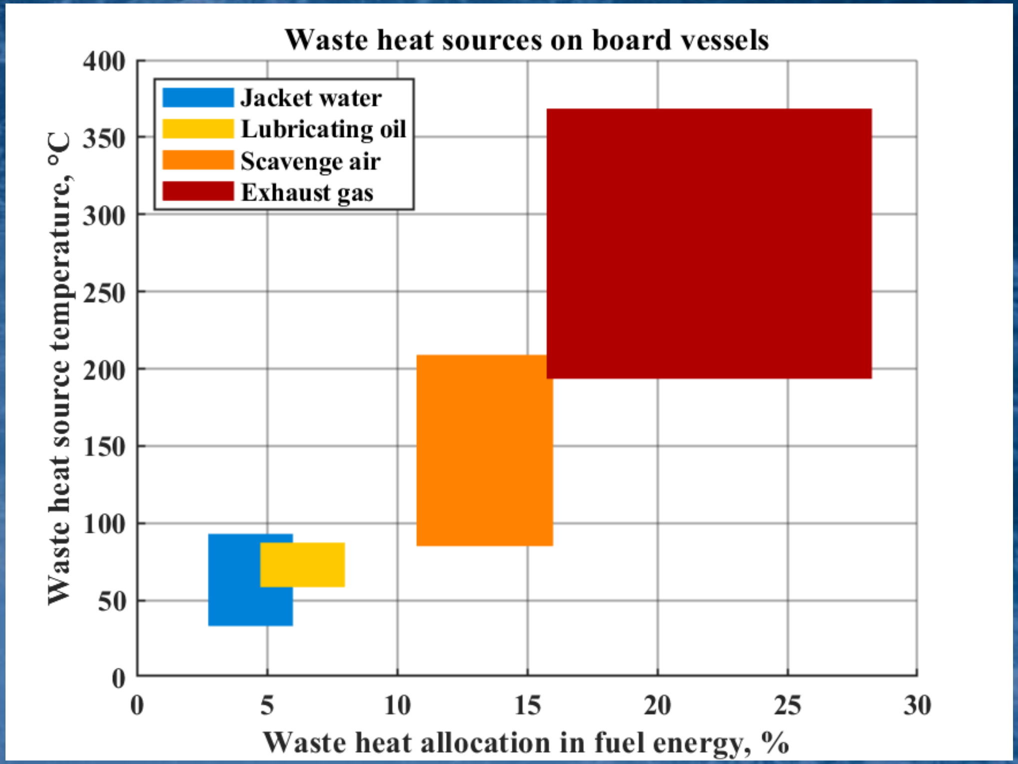
On-board energy system and waste heat



Schematic of an archetypal on-board energy system of a mechanically propelled vessel



Temperature levels and waste heat amounts for the main sources on board vessels

Pillow plate latent heat thermal energy storage

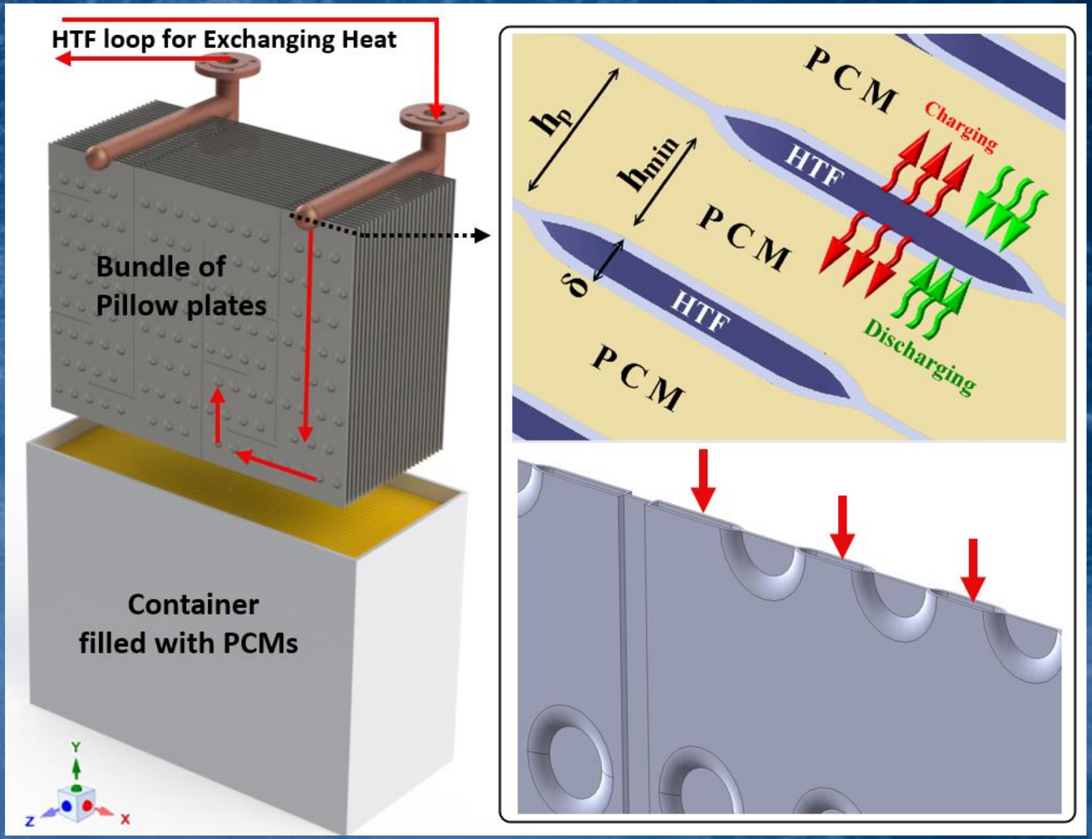
Thermal energy storage (TES) systems are innovative waste heat recovery (WHR) solutions:

- Solving the discrepancy in time between the availability of thermal energy at a certain heat source and the heat demand elsewhere
- Smoothing fluctuations of waste heat availability

Latent heat thermal energy storage (LHTES) systems use phase change materials (PCMs) to absorb and release energy at nearly constant temperatures

Thermal energy storage:

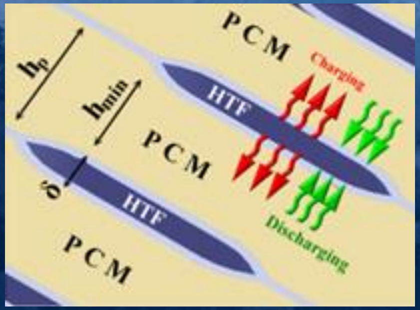
- Primarily as latent heat of fusion of the PCM
- Secondly as sensible heat of materials

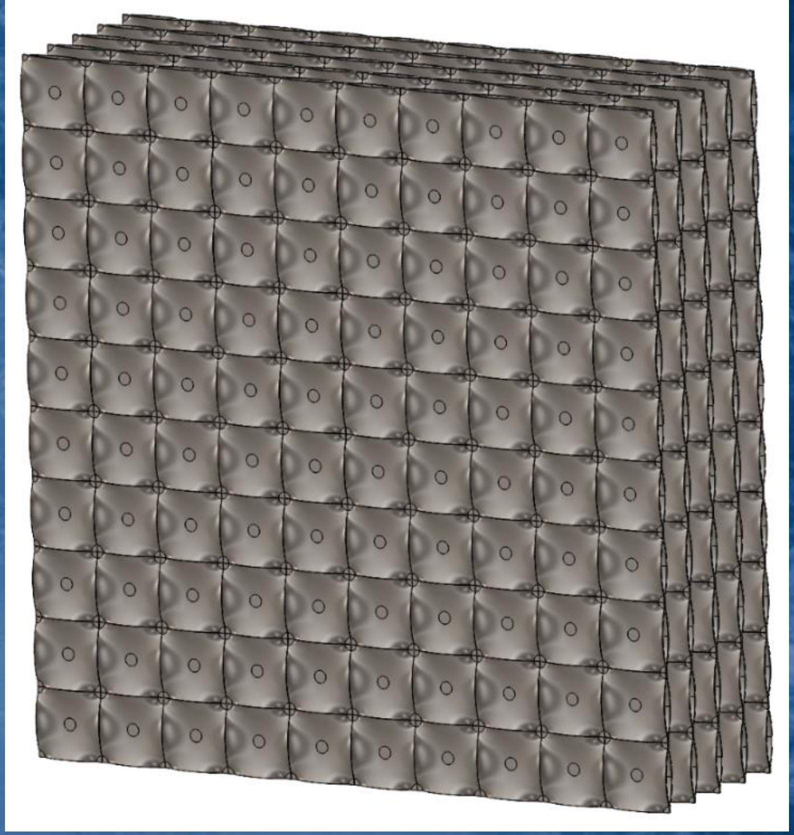


Schematic of the pillow plate latent heat thermal energy storage (PP-LHTES) system

Pillow plate geometry

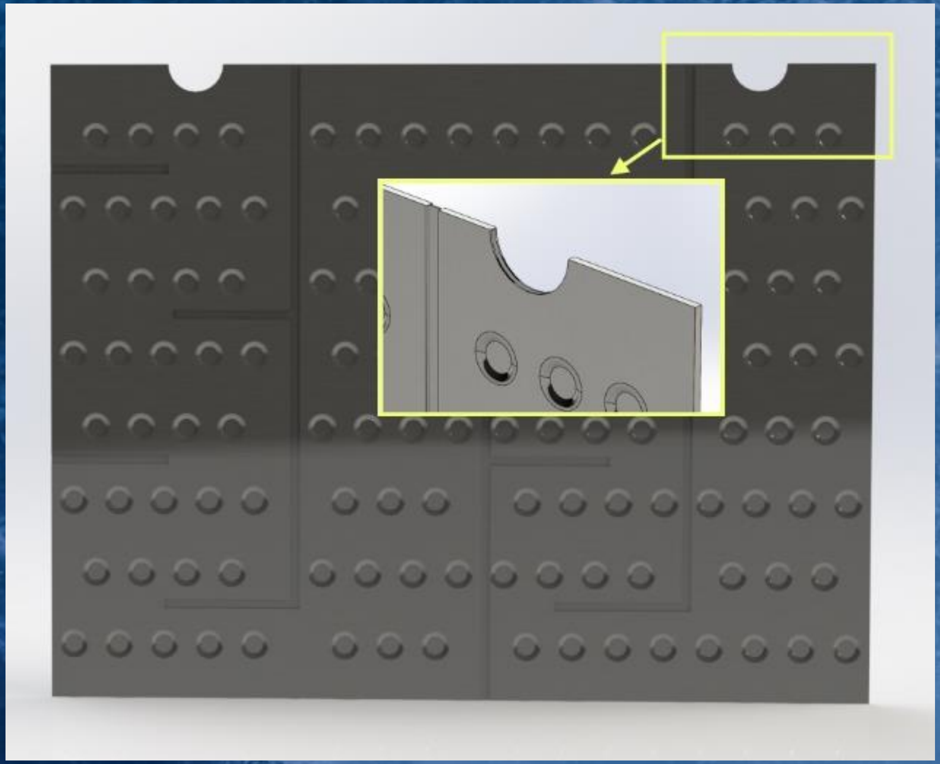
Parameter	Value
Pillow Plate number (n_p)	10
Pillow plate length (L)	700 mm
Pillow plate width (W)	900 mm
Inlet and outlet pipe diameter (D_e)	55 mm
Plate pipe diameter (D_p)	60 mm
Welding external diameter (D_{we})	32.64 mm
Welding internal diameter (D_{wi})	20.00 mm
Pillow plate internal gap (δ)	10 mm
Pillow plate distance (h_{min}, h_p)	12 mm, 15 mm
Plate thickness (t_p)	1 mm

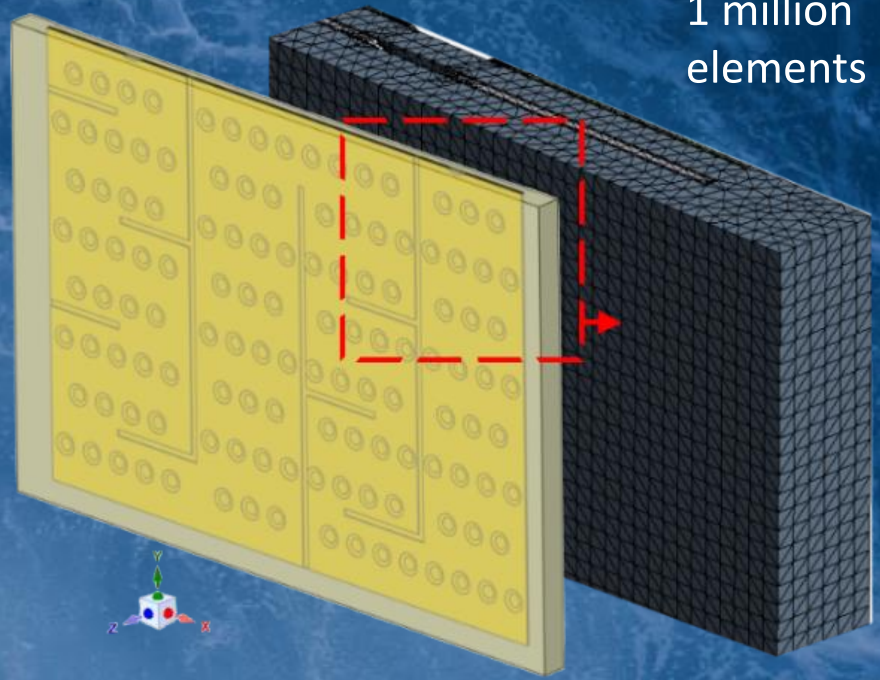




Example of five parallel pillow plates (PPs), each comprising 100 elements

Computational fluid dynamics (CFD) model





Pillow plates with identical geometry

Equivalent flow conditions of the heat transfer fluid (HTF)

Limited effects of heat losses through the tank walls on heat exchange between HTF and PCM

Domain with half of a pillow plate and the PCM

Modelling and boundary conditions

The solidification and melting model is applied to solve the thermodynamics of phase transition of the PCM

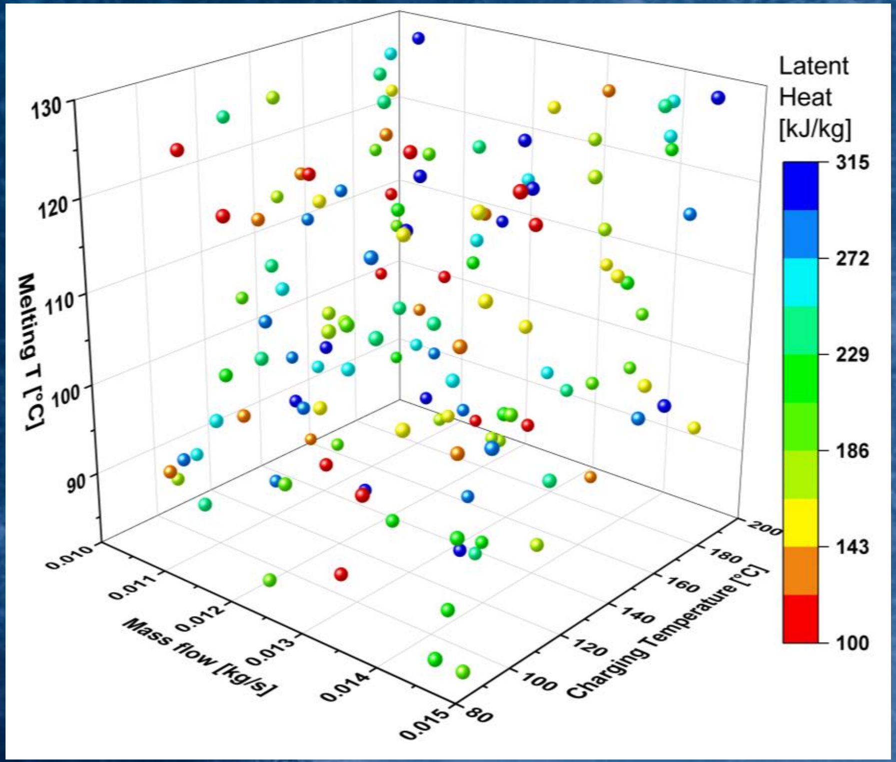
The enthalpy-porosity formulation is used to determine the phase of the mushy zone of the material subject to phase change

The mushy zone is modelled as a porous zone with porosity equivalent to the liquid fraction

$$\begin{cases} \int_{T_0}^{T_{pcm}} (\rho c_p)_{pcm} dT & T_{pcm} < T_{sol} \\ \int_{T_0}^{T_{pcm}} (\rho c_p)_{pcm} dT + \frac{\rho L}{T_{liq} - T_{sol}} (T_{pcm} - T_{sol}) & T_{sol} < T_{pcm} < T_{liq} \\ \int_{T_0}^{T_{pcm}} (\rho c_p)_{pcm} dT + \rho L & T_{pcm} > T_{sol} \end{cases}$$

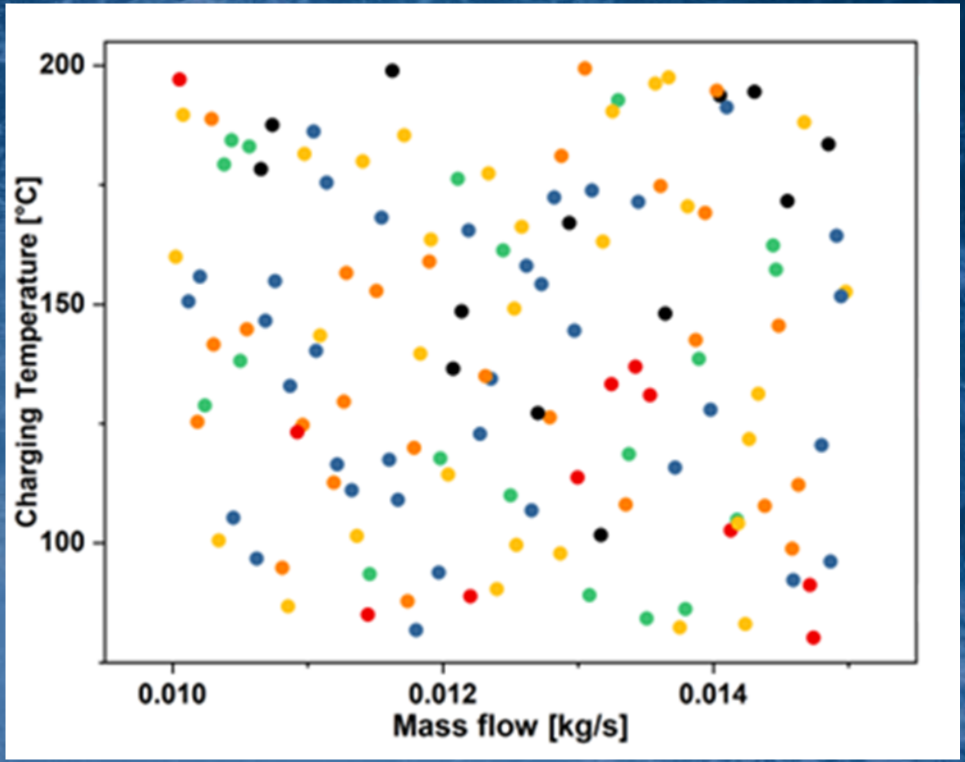
Parameter			Value
HTF (Therminol 66)	C_p [kJ/kgK]	373K	1.84
		473K	2.19
	Density, ρ [kg/m3]	373K	955
		473K	885
PCM	C_p [kJ/kgK]		1.5 … 2.3
	Thermal conductivity [W/mK]		0.36 … 0.51
	Density [kg/m^3]		900 … 1600
	Latent heat (LH) [kJ/kg]	PlusICE: H105, H115, H120	125, 100,120
		PlusICE: A82, A95,	240, 250
		PlusICE: X80, X90, 120, 130	160, 170, 185, 315
		PlusICE: S83, S89	100, 145
		Rubitherm RT: 100, 111	120, 190
	$T_{melting}$ [°C]	PlusICE: H105, H115, H120	105, 115,120
		PlusICE: A82, A95,	82, 95
		PlusICE: X80, X90, 120, 130	80, 90, 120, 130
		PlusICE: S83, S89	83, 89
		Rubitherm RT: 100, 111	100, 111

Design space definition



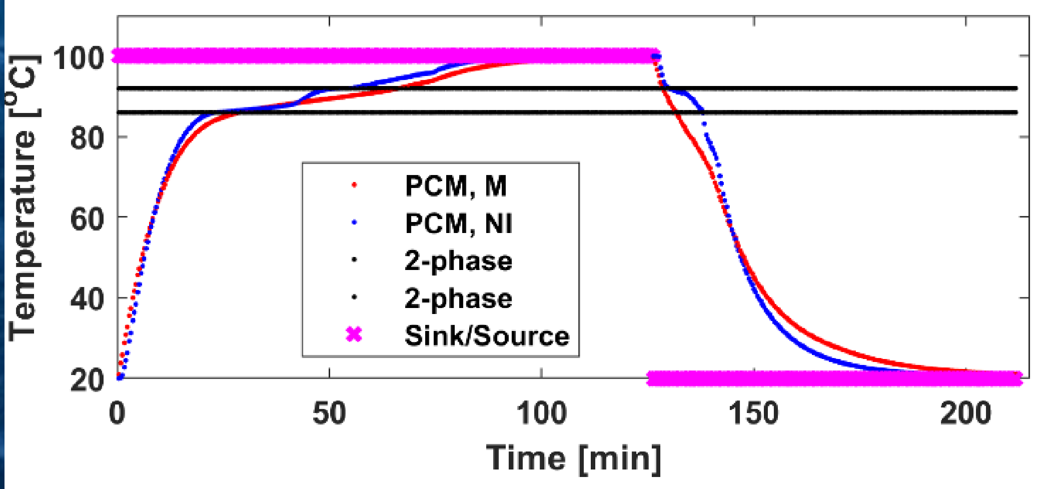
Latin Hypercube Sampling (LHS)

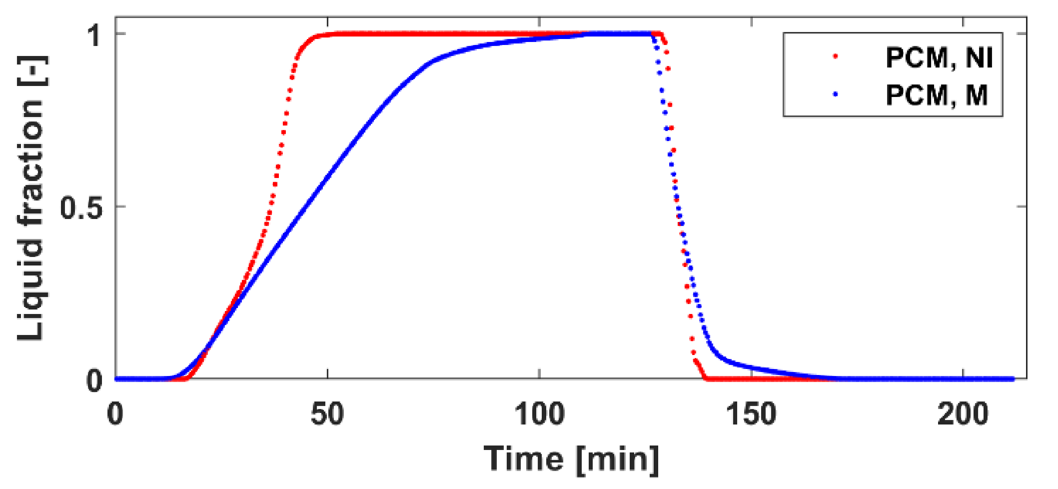
LHS is applied to generate 100 sets of random samples across 4 dimensions



Each randomly generated parameter is compared with commercially available PCMs

Charging and discharging phases



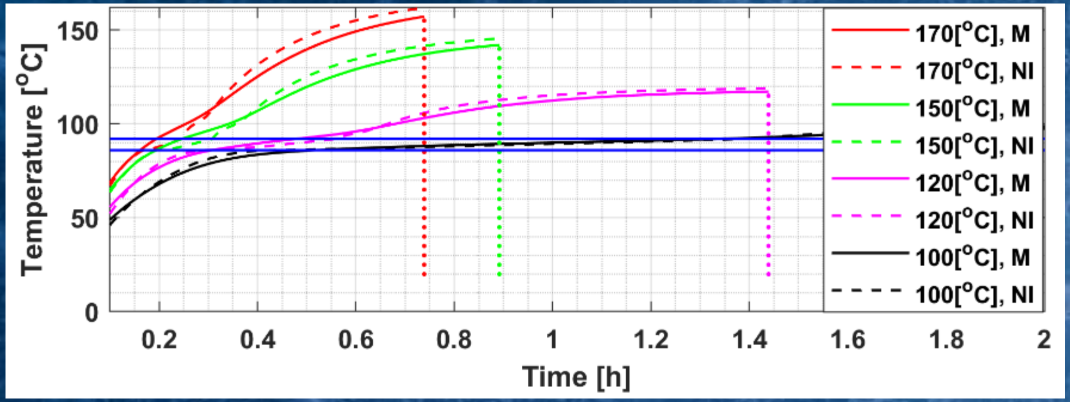


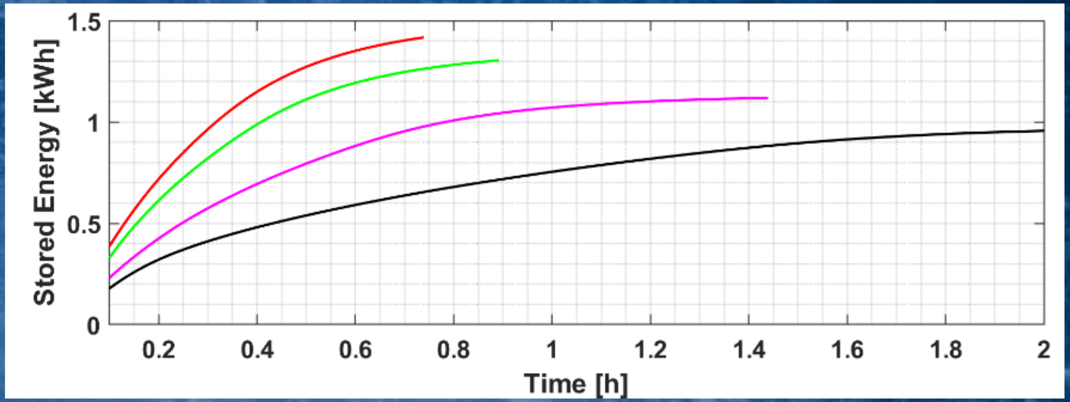
In the mushy zone, the temperature remains within the bounded temperature interval of the solidification and melting values

The melting and solidification of PCM take less time near the inlet (NI) of the HTF compared to the mean value (M) of the PCM domain

Reaching the fully charged state is achieved in 2 h

Heat source temperature effects





A higher source temperature results in a shorter charging time for a greater temperature difference

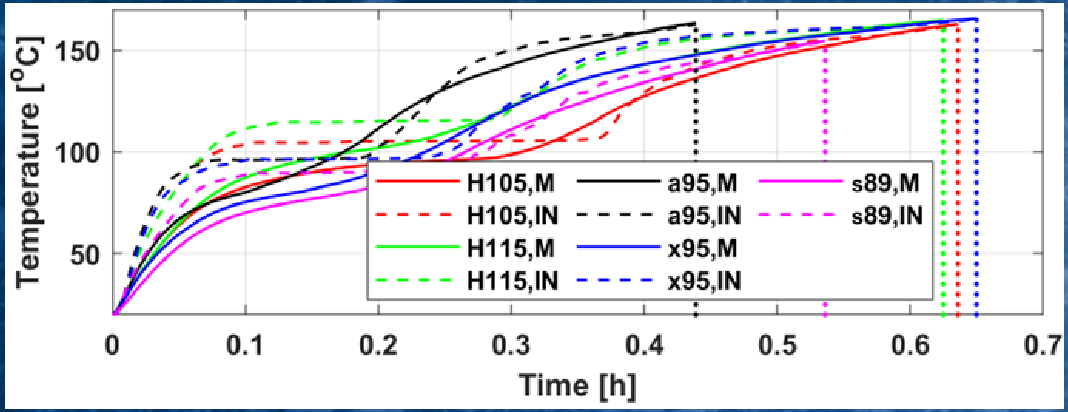
A source temperature of 170 ◦C halves the charging time compared to the case of 120 ◦C

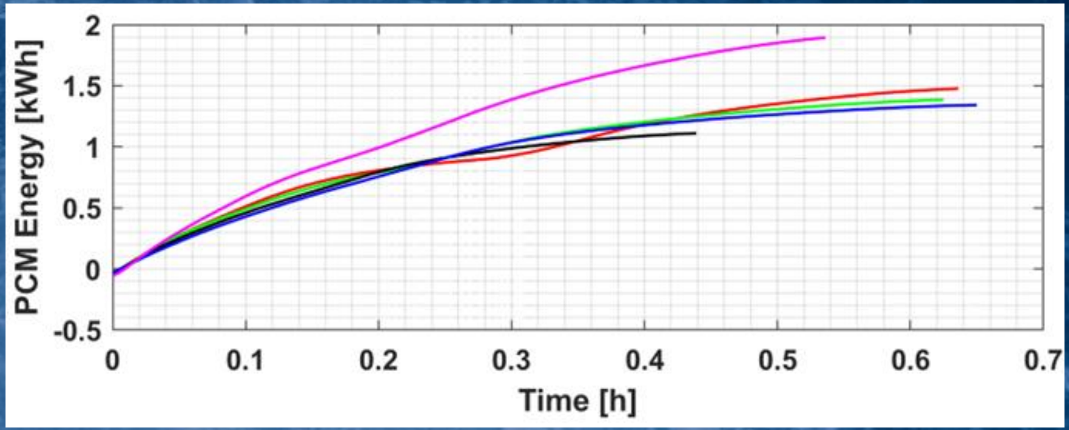
The rise in source temperature increases the storage of sensible heat

The storage capacity improvement is 50% when the source temperature is increased from 100 to 170 ◦C

The source temperature condition is usually imposed by the waste heat source of the vessel

Phase change material effects





Organic PCMs: A-type

Inorganic PCMs: H-type

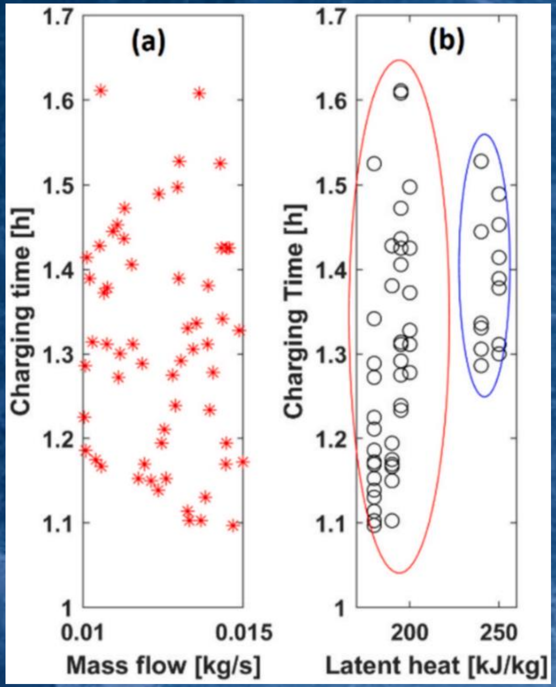
Hydrated salts: S-type

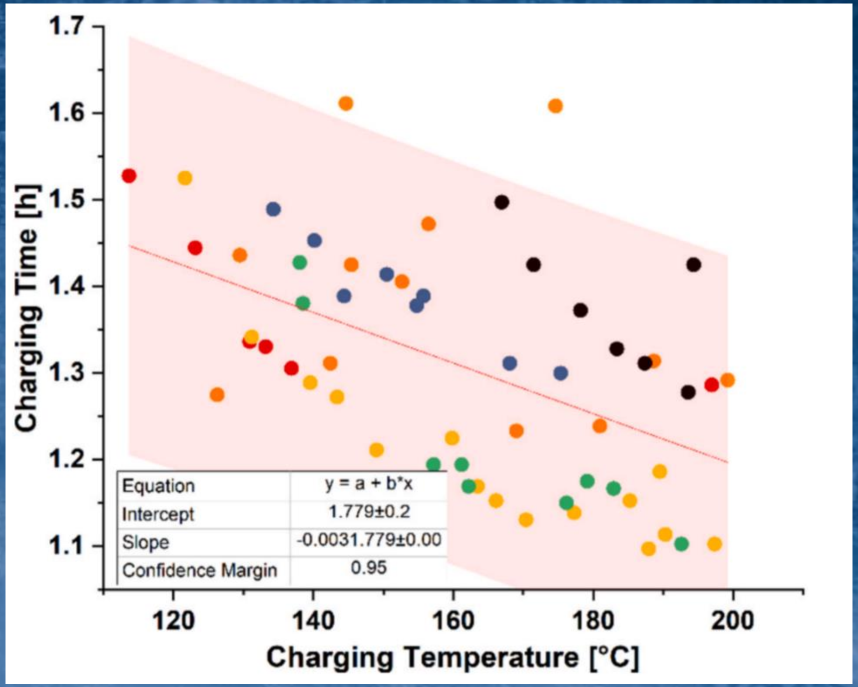
Solid–solid PCMs: X-type

The energy storage capacity of the LHTES system depends on the specific heat capacity and latent heat of fusion of the storage material

The choice of the phase change material affects the charging time

Sensitivity analysis



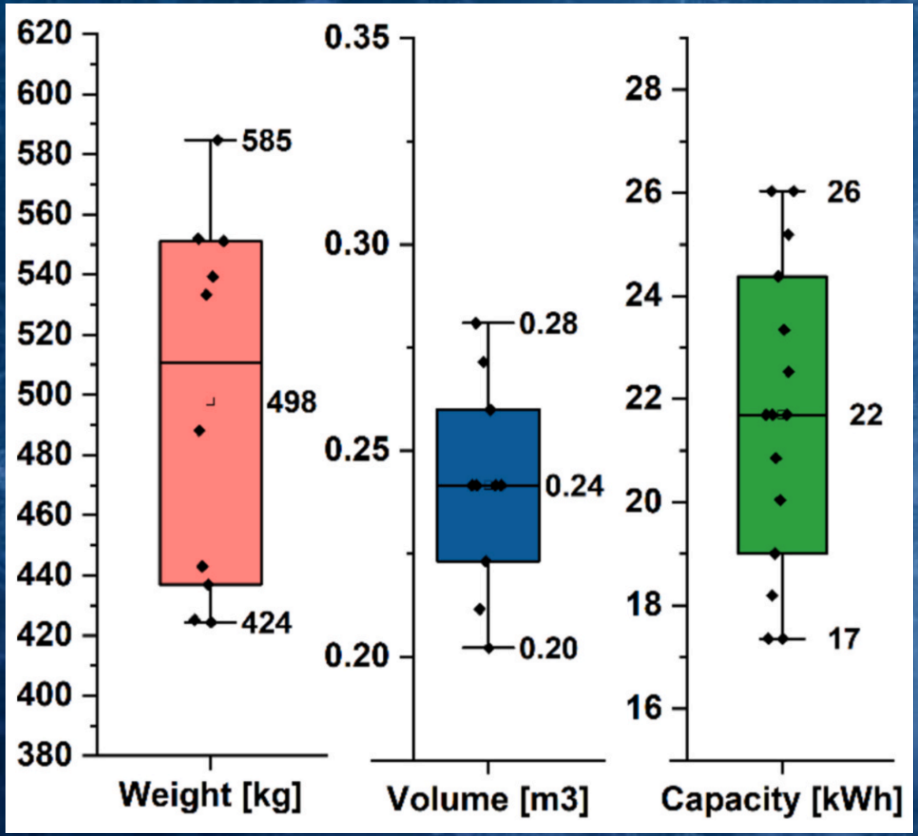


The MFR reduces the charging time for a configuration but not for the entire set

The charging time increase of 15% for a PCM with double the value of latent heat

A regression function expresses the charging time based on the source temperature

PP-LHTES module performance

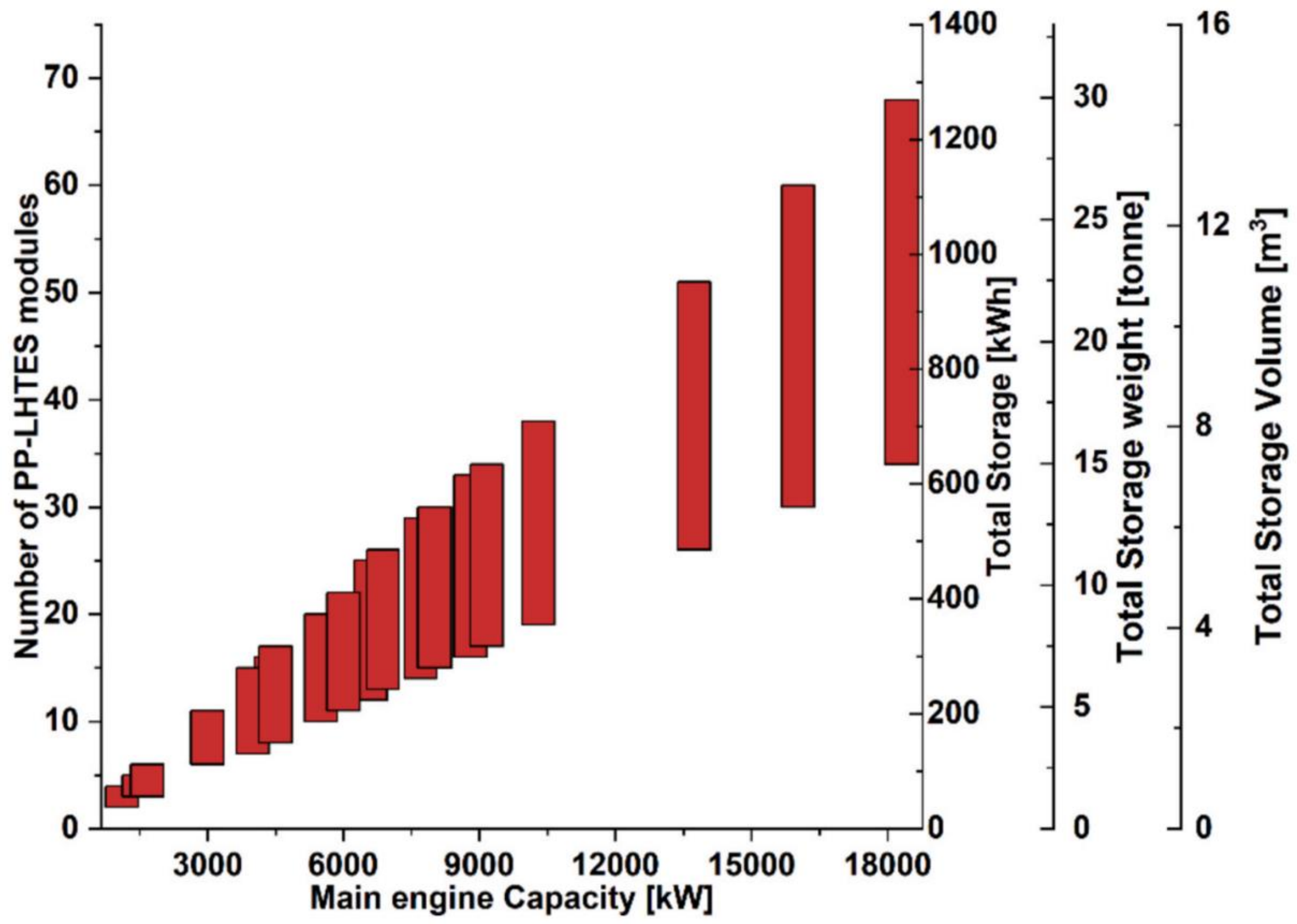


Parameter	Average value
Mass, kg	498
Volume, m^3	0.24
Energy storage capacity, kWh	22
Energy storage density, kWh/m^3	90

The configuration of a PP-LHTES unit depends on the specific application

The geometry of the pillow plates and the phase change material are designed based on the heat source available

PP-LHTES on board vessels



The number of required modules is between 2 and 60 depending on the vessel scale

The mass of the PP-LHTES system is 30 t and its volume is 16 m^3 for a vessel with a main engine capacity of 18 MW

The mass and volume are 15% and 5% of the mass and volume of marine engines

Additional fuel consumption of 0.003%

Increase of 0.2% in the capital cost of the vessel

Conclusions and current activities

Conclusions:

- The waste heat sources on board vessels and their availability were determined
- The operation of a PP-LHTES module was analysed with computational fluid dynamics
- A sensitivity analysis was conducted with CFD to evaluate the effects of the temperature of the heat source, the phase change material, and the mass flow rate of the heat transfer fluid
- The average values of the PP-LHTES module are a mass of 498 kg, an energy storage capacity of 22 kWh, and an energy storage density of 90 kWh/m^3
- The number of PP-LHTES required for on-board applications was assessed

Current activities:

- A PP-LHTES prototype with an energy storage capacity of 25 kWh has been designed, assembled, and initially tested

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Research Paper

Latent heat thermal energy storage system with pillow-plate heat exchangers topology – Assessment of thermo-fluid dynamic performance and application potential☆

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A R T I C L E I N F O

Keywords:
Thermal energy storage
Waste heat recovery
Topology
PCM Phase Change Materials
Numerical modelling
Decarbonization

A B S T R A C T

This research investigates the novel concept of pillow plate latent heat thermal energy storage (PP-LHTES) for storing process heat and/or waste heat at medium temperature, up to around 200 °C, and with a focus on mobile TES applications, such those in the maritime sector. The work introduces a novel methodology that combines computational fluid dynamics (CFD) with reduced-order modelling (ROM) techniques to evaluate the thermo-economic performance of PP-LHTES at the prototype scale (∼102 kWh) and predict its potential at full scale (∼MWh). These are the key aspects of novelty of the research. The study focuses on the impact of key technical factors, including the selection and thermophysical properties of the phase change material (PCM), its melting temperature and latent heat of fusion, the operating temperature, and the flow rate of the heat transfer fluid. Furthermore, the cost-effectiveness of PP-LHTES was examined by evaluating nine design parameters, such as the number of pillow plates and the cost per unit of PCM. Findings indicate that PP-LHTES appear to have a competitive advantage in volumetric energy storage density at the system level (∼89 kWh/m^3), making it more compact than other LHTES solutions (∼53 kWh/m^3) with a similar specific capital cost (∼200 €/kWh). The PP-LHTES module weighs 500 kg, occupies 0.25 m^3, and provides an energy storage capacity of 17 to 22 kWh. The scalability of the design is investigated and results emphasize the its versatility. The mass-averaged volumetric energy storage density is comparable to existing LHTES systems (∼50 kWh/t). This is due to the distinctive design of pillow plate heat exchangers, which integrate heat transfer fluid channels and extended heat transfer surfaces into a compact structure. This design increases energy density at the system level, reduces the overall footprint, and enhances the feasibility of deploying TES devices in end-user applications.

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