UNIVERSITÀ DEGLI STUDI FIRENZE DIEF DIPARTIMENTO DI INGEGNERIA INDUSTRIALE

Thermo Group THERMODYNAMICS AND HEAT TRANSFER

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THUNDER

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Data centre waste heat recovery through thermochemical energy storage and high temperature heat pump: preliminary analysis

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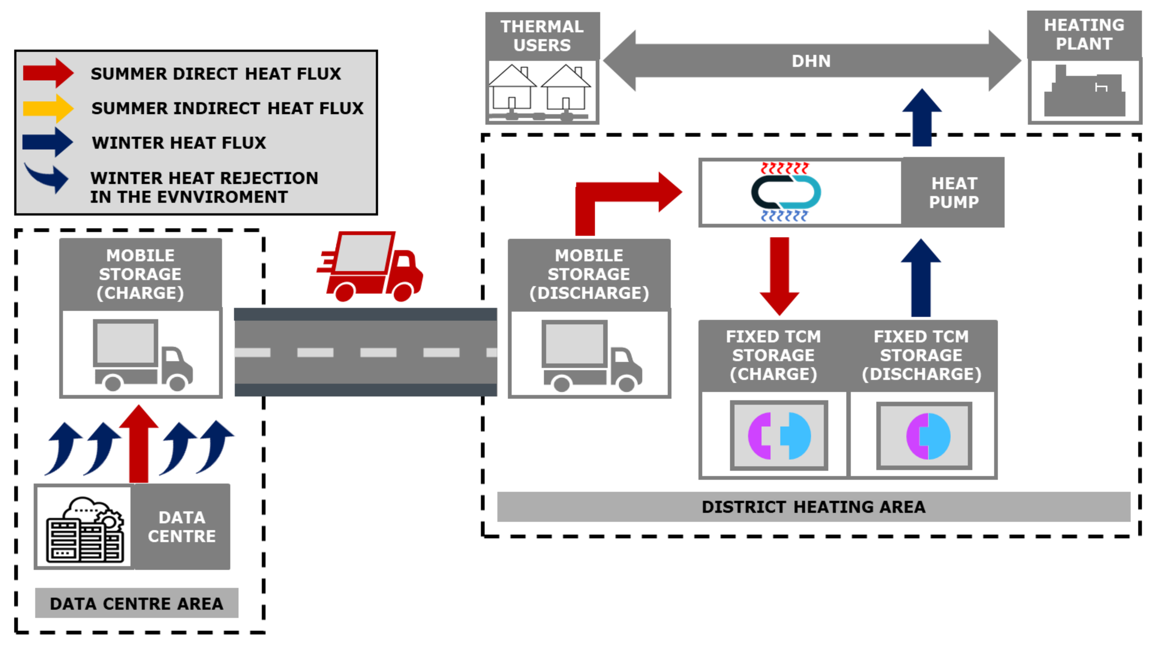
Context

THUNDER PROJECT **

- **Aim**: develop **sustainable waste heat recovery** and **seasonal storage** solutions **tailored for data centres in urban environments**, enabling the **supply of heat to nearby DHNs**, while simultaneously providing cooling services to the DCs
- **UNIFI Main Focus**: Thermochemical material (**TCM**) based storage systems cutting-edge technology utilizes **specially selected materials** designed **to boost storage capacity through enhanced heat and mass transfer processes**, while **minimizing thermal losses to near-zero**

  When combined with **thermal upgrade devices** like high-temperature heat pumps (**HTHPs**), these systems leverage **chemical reactions and sorption processes** to offer a next-generation, efficient, and **compact storage solution**.
- This approach effectively **harnesses the low-grade DC-WH**, **accumulating it during the summer** and **storing it for release into the DHN during the winter**



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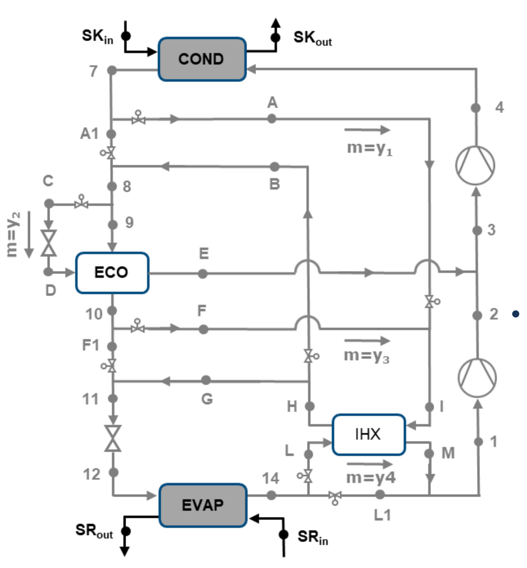
Methodology

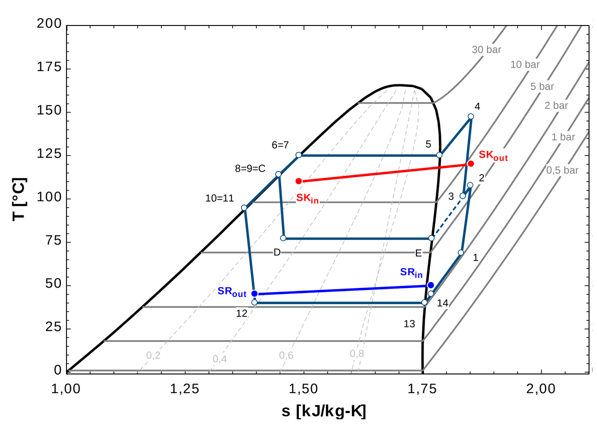
HIGH-TEMPERATURE HEAT PUMP



Design conditions:
- Waste heat capacity: 21.6 kW
- Heating capacity: **40 kW**
- Outlet sink temperature: **up to 140 °C**
- Temperature Lift: up to 100 K

- Working fluid: **R1233zd(E)**
- Compressor: Volumetric **Scroll**

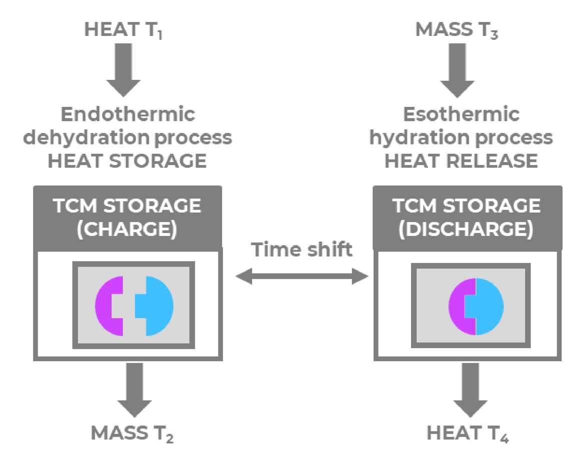
Performance enhancing components:
- Internal Regenerative Heat Exchanger (**IHX**)
- Economiser (**ECO**)

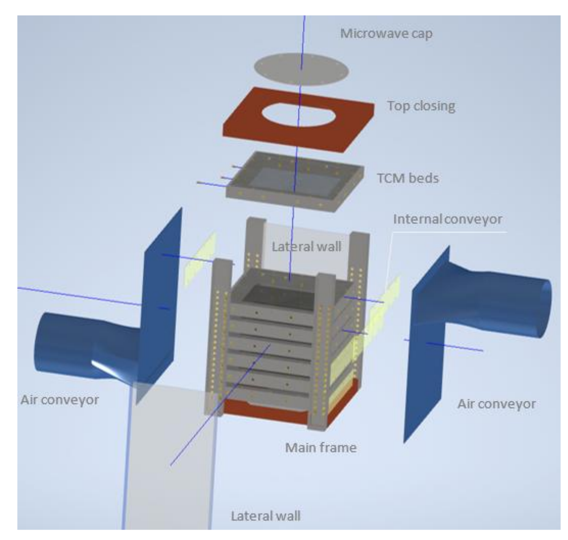


THERMOCHEMICAL ENERGY STORAGE

Objective:
- Performance analysis of a composite material: **expanded vermiculite** impregnated with **calcium chloride** ($CaCl_2$), chosen for its high sorption capacity, favorable heat release, and mechanical stability.
- Composite material is sandwiched between two air flow channels.

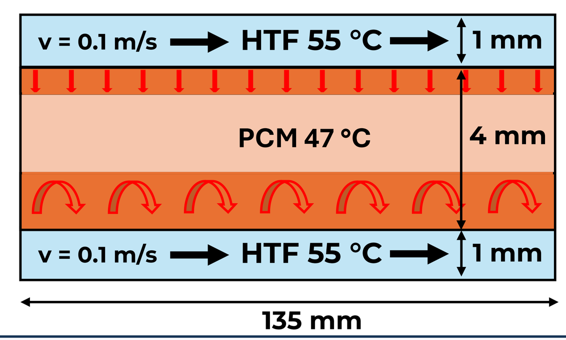
Model Assumptions:
- The material bed is modeled as a homogeneous porous medium with constant thermo-physical properties.
- TCM particles are not dragged by the airflow.
- Permeability and porosity (set to 0.3) are constant over time.
- Heat transfer by radiation is neglected due to the low temperature range.
- Only the discharging phase is simulated, assuming the material is initially fully dehydrated and exposed to cold, humid air.





PCM ENERGY STORAGE

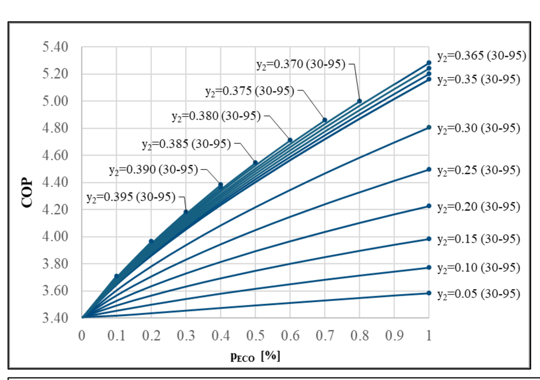
- Full stacks consist of PCM bags with water channels in between, where water acts as the working fluid to exchange heat with the PCM.
- Instead of modeling the entire stack, a representative section of the geometry is extracted and symmetry boundary conditions are applied.
- The gravity vector is perpendicular to the main heat flow direction that creates an asymmetric situation
- In the **upper region**, buoyancy opposes heat flow, so **conduction dominates**
- In contrary in the **lower region**, buoyancy assists heat flow, promoting **natural convection**.

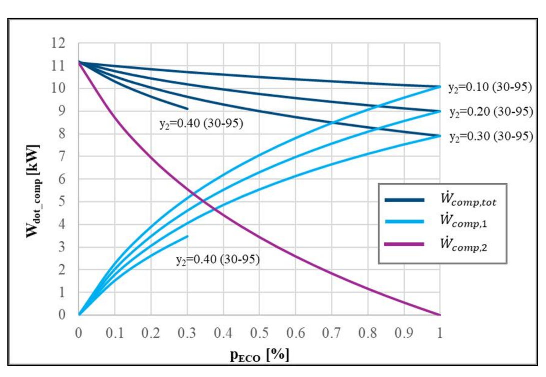


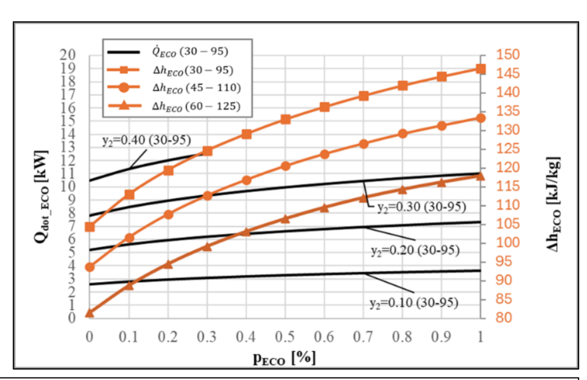
Results

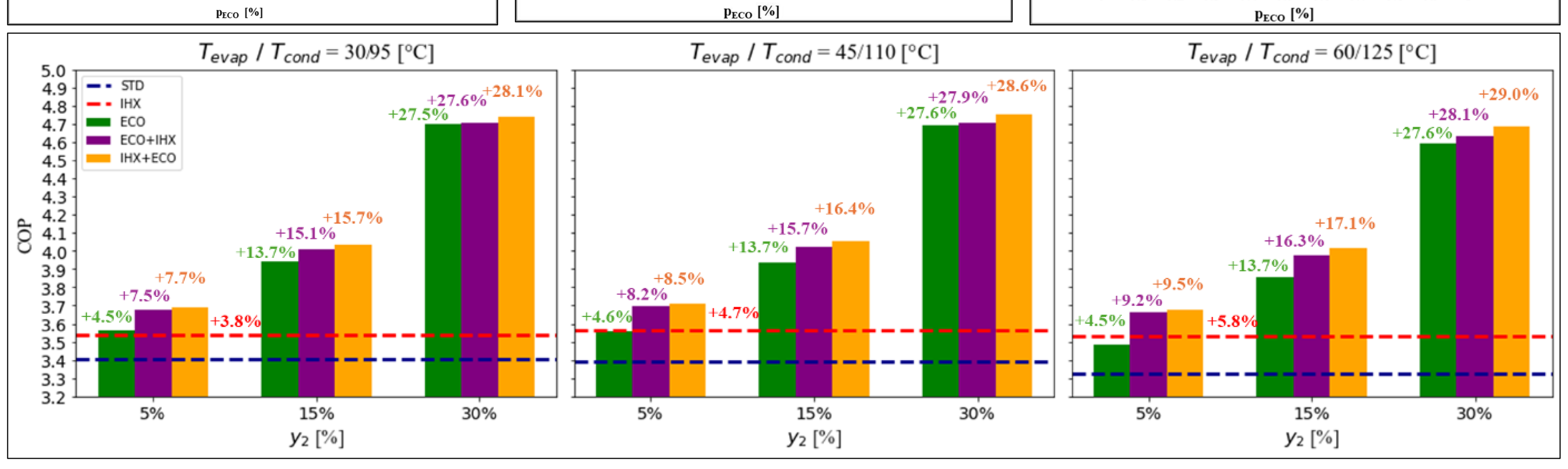
HIGH TEMPERATURE HEAT PUMP

- The COP increases with rising ECO pressure and with a greater extracted fraction
  - Power absorbed by the 1st stage ↑ with the ECO pressure and ↓ with the extracted fraction
  - Power absorbed by the 2nd stage ↓ with the ECO pressure and is not affected by the extracted fraction
- y_2 influences the maximum pressure allowable at the ECO: ↓ throttling, the available latent heat of evaporation ↑
  - The thermal power harnessed in the ECO is the product of the available latent heat and the extracted mass flow rate and ↑ with both variables: it would be sufficient to subcool the primary flow below the evaporation level.
- Using a regenerative heat exchanger (IHX) improves HTHP performances
  - At low extraction rates, the position of the IHX has a negligible impact
  - If y_2 ↑, placing the IHX after the ECO is almost useless: the entire available subcooling is saturated by the ECO
  - placing the IHX before the ECO, ↓ the maximum y_2 , an initial subcooling is already achieved in the IHX
  - The influence of the IHX ↑ with rising condensation temperature







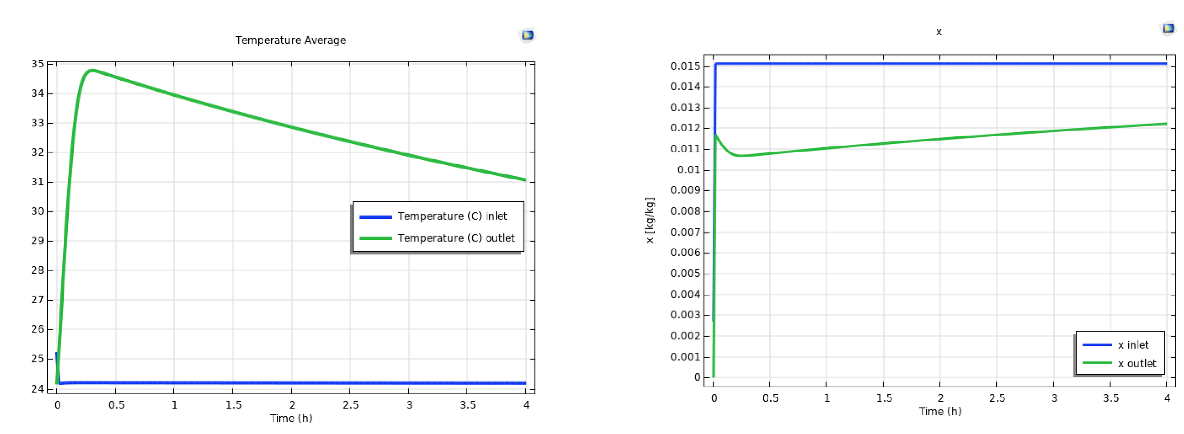


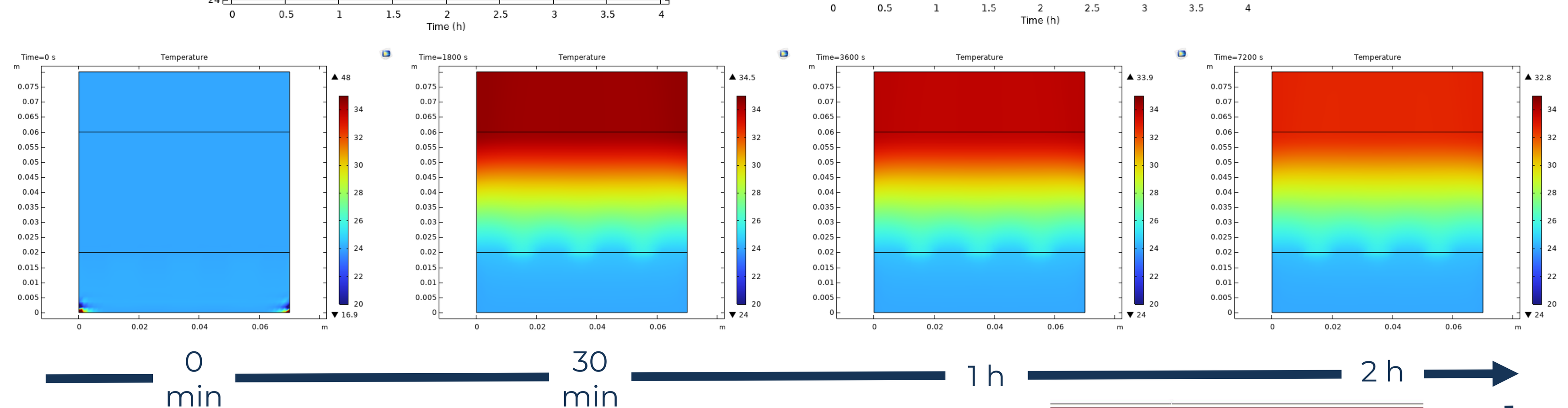
THERMOCHEMICAL ENERGY STORAGE

Air Temperature Behaviour:
- Rapid rise in outlet temperature to ~34.7°C within the first 30 min, indicating immediate exothermic hydration.
- Gradual temperature decrease afterward as the material becomes saturated.
- Inlet air temperature remains steady at 24°C.

Humidity Ratio Behaviour:
- Sharp initial drop in outlet humidity ratio due to effective vapor adsorption.
- Slow increase over time, showing reduced sorption capacity as hydration progresses.

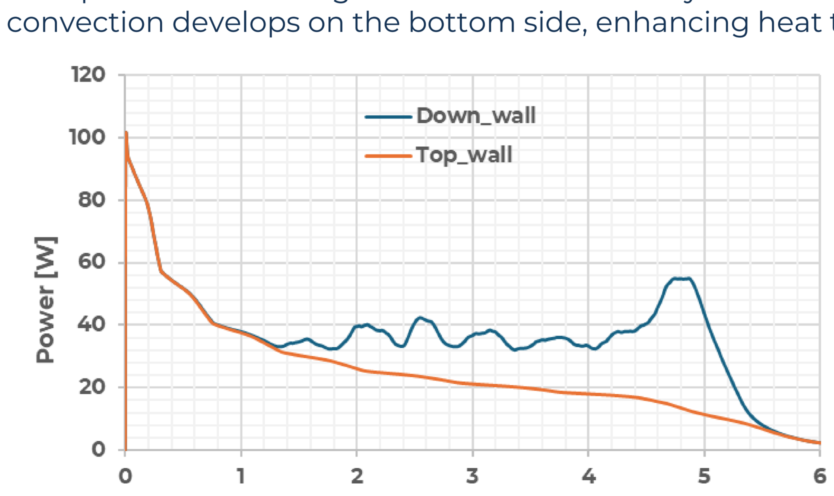
Internal Temperature Distribution:
- Initial uniform temperature across the system (~24°C).
- A thermal front forms and moves upward through the composite layer as the reaction proceeds.
- Temperature exceeds 33°C in the upper region over time, aligned with the direction of airflow.
- Confirms strong thermal response of the material and effective layered design of the device.

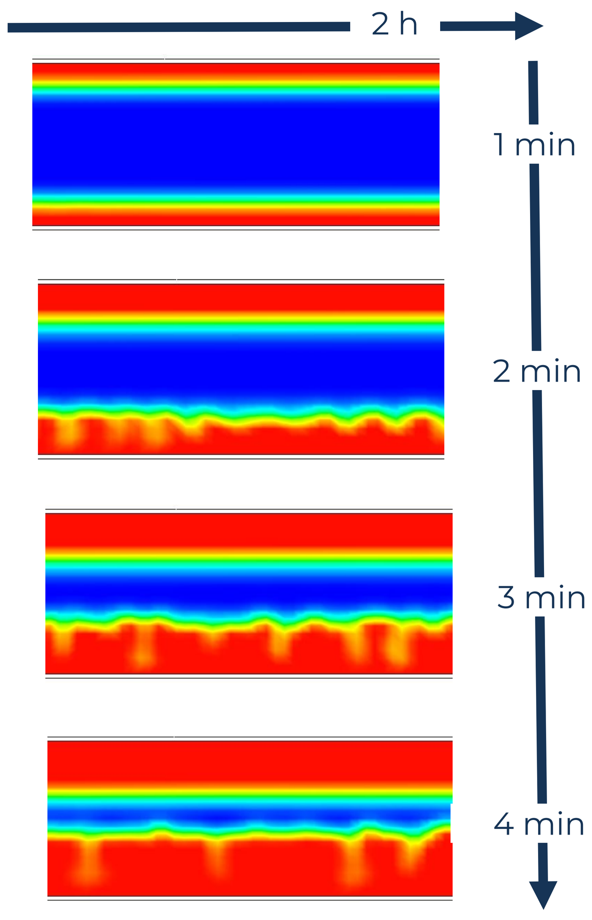




PCM ENERGY STORAGE

- Full melting is achieved at around 5 minutes.
- Asymmetry in melting behaviour: on the top side, the dominant heat transfer mode is pure conduction, since buoyancy forces oppose the temperature gradient, limiting convection. On the bottom side, we observe both conduction and natural convection, as buoyancy-driven flow enhances heat transfer from the water to the PCM
- Bottom wall power remains higher and more oscillatory than the top wall: natural convection develops on the bottom side, enhancing heat transfer.





Conclusions

- Waste heat recovery is a practice with significant economic potential that can also mitigate urban heat island effects
- Space constraints suggested the use of a mobile energy storage based on PCM to indirectly connect the data centre and the district heating facilities. The use of thermochemical energy storage is fundamental to temporally shift the waste heat summer harvesting from the data centre and its winter reuse to supply the district heating network
- The constraint to the reutilisation of DC-WH is related to its low rejection temperatures (30–40 °C). When combined with thermochemical energy storage characterized by high temperature charge, HTHP are required
- The addition of auxiliary components, such as an ECO and an IHX, enhances performance The ECO is particularly beneficial, as it not only recovers throttling losses through increased subcooling but also reduces power consumption in the first compression stage, without influencing negatively the compressor discharge temperatures. The COP improves significantly, with gains exceeding 25% for secondary mass flow rates of 30%
- The model, developed in the COMSOL Multiphysics software, incorporated coupled physics for fluid flow, heat, and mass transfer in porous media, and the effect of water vapour capture through a custom-defined heat source. The obtained results demonstrated a significant thermal response of the system, with outlet air temperatures reaching up to 34.7°C from an inlet of 24°C. The vapour concentration profiles confirmed the effective moisture uptake and gradual saturation of the material
- CFD modeling of the PCM stack, performed in ANSYS Fluent, highlighted the importance of considering the gravity vector

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