Performance enhancement of a Latent Heat Thermal Energy Storage for Domestic Hot Water production

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COMBIOTES Project

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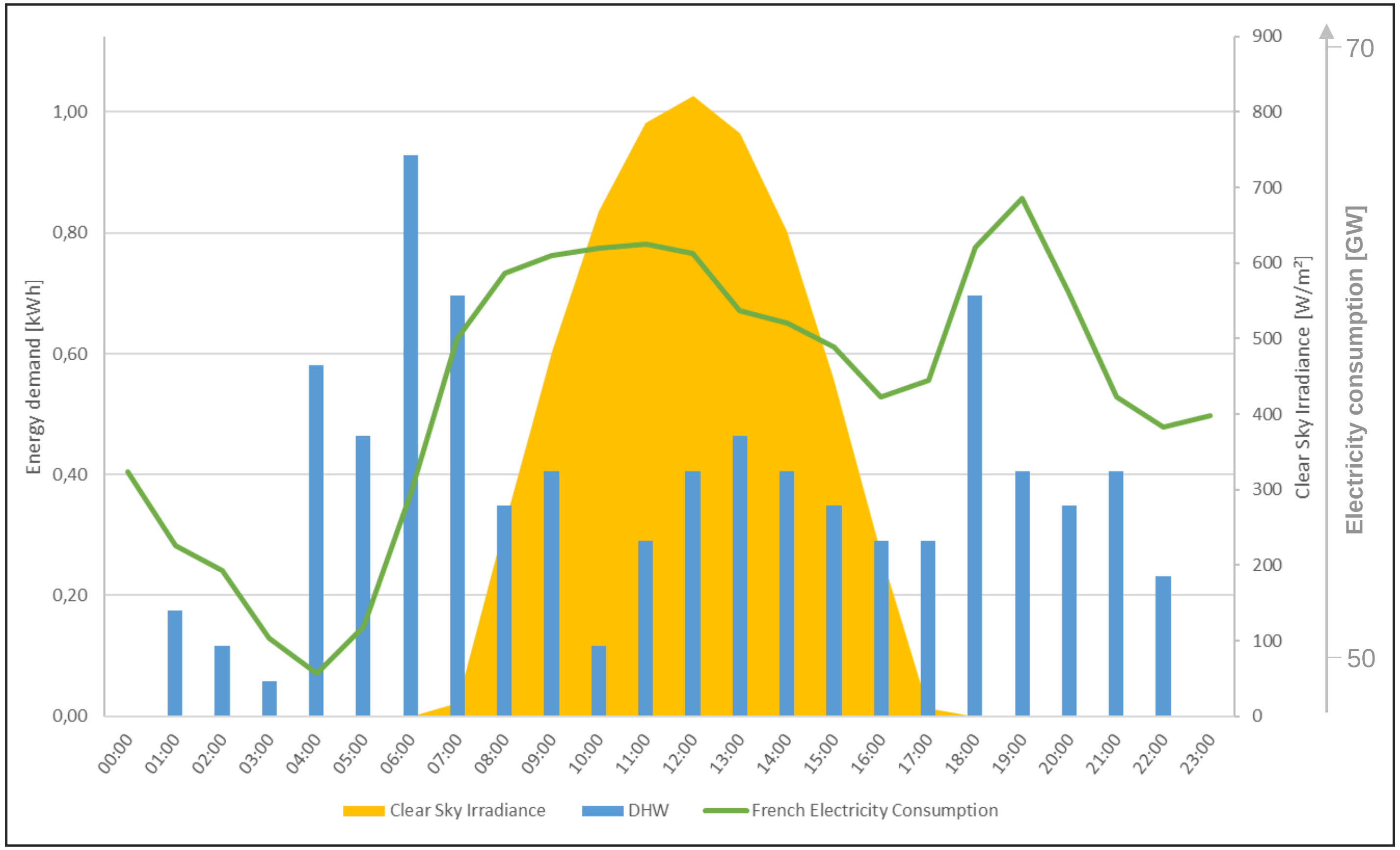
Why Thermal Energy Storage for Domestic Hot Water Production?



Own calculations based on data from PVGIS, DHWcalc and RTE (French TSO)

- Peaks of Domestic Hot Water (DHW) consumption in the morning and in the evening
  - Simultaneous with peak of electricity demand
  - In opposite phase with solar profile

Thermal storage at residential scale

- Time-decoupling between heat production and consumption

➔ Combination with solar thermal
➔ Combination with heat pumps

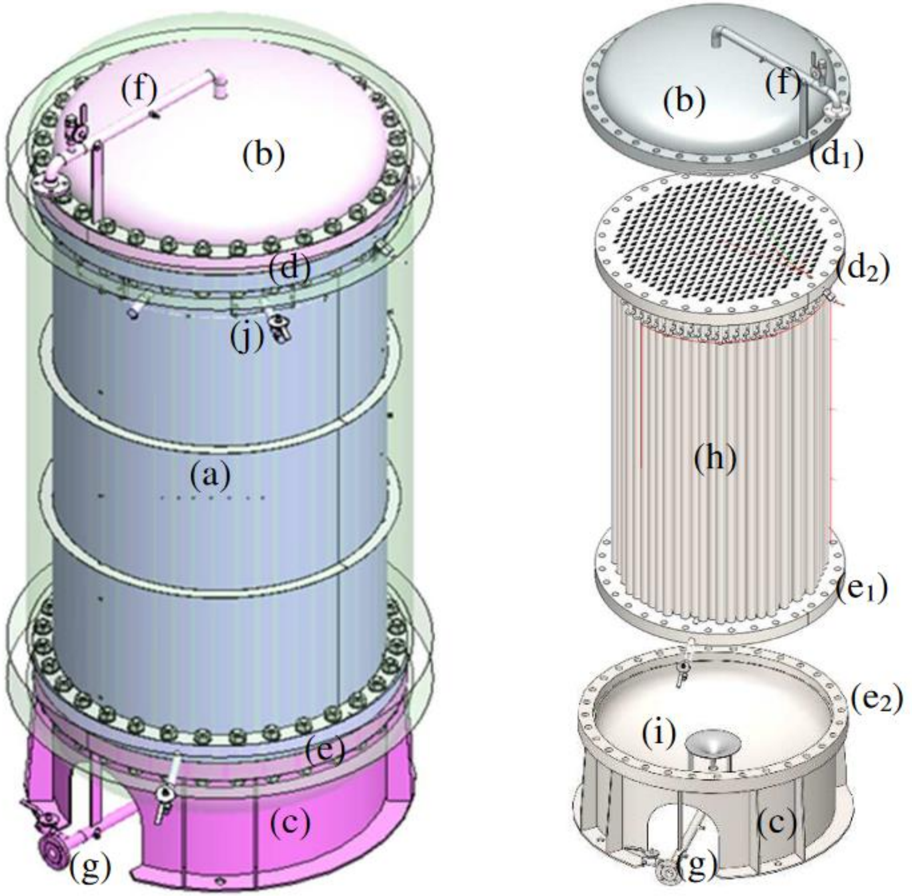
Objective of the study

- Assessment of the **performance in discharge** of a **Latent Heat Thermal Energy Storage** for **DHW** production
- Investigation of design factors to enhance performance

Use Case

- Thermal Energy Storage (TES) to provide **Domestic Hot Water (DHW)** for a **single-family house**
- **Requirements :**
  - Capacity : **9kWh** (Daily DHW need for 5-persons household - ADEME, 2022)
  - Draw off flow rate : **12 L/mn**
  - Draw off temperature : **40°C**
  - Water input temperature : 12°C
- **Charging phase** of the storage is not studied here (internal electrical charge assumed)
- Assumption that TES initial temperature is **75°C**

Storage Design

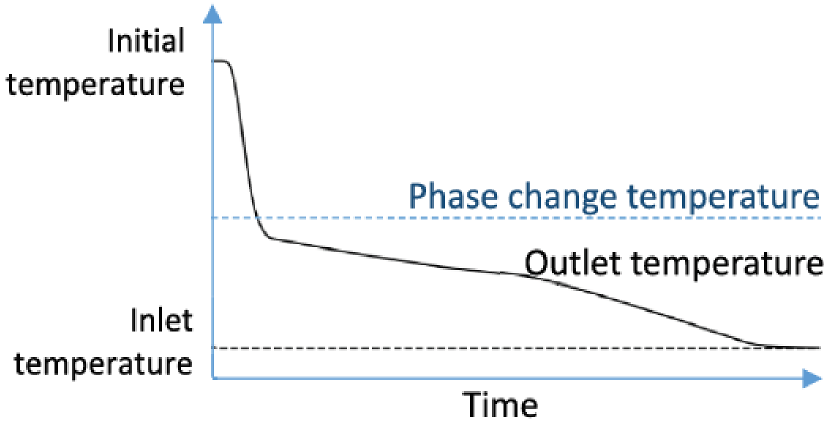


Schematic of a shell-and-tube Latent Heat TES (Bentivoglio et al, 2021, hal-03492919)

- Based on **Shell-and-tube** Heat Exchanger concept
- Heat Transfer Fluid (HTF) = Water flows inside **finned tubes**
- Tube bundle (h) is surrounded by Phase Change Material (PCM) embedded in the shell (a)
- **Inserts** are placed inside the tubes (reduction of hydraulic diameter and thus Grashof number ➔ forced convection flow regime)

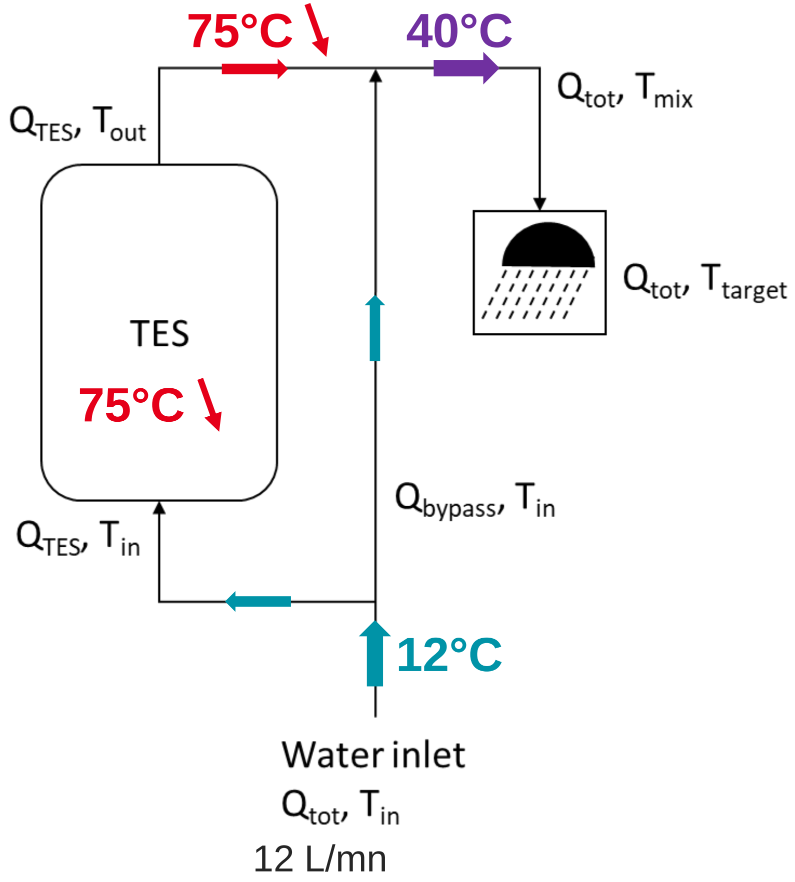
System

Latent Heat TES outlet temperature decreases with time in discharge



Typical evolution of Latent Heat TES outlet temperature during discharge

Need to partly bypass TES in order to reach a constant temperature at the draw-off point



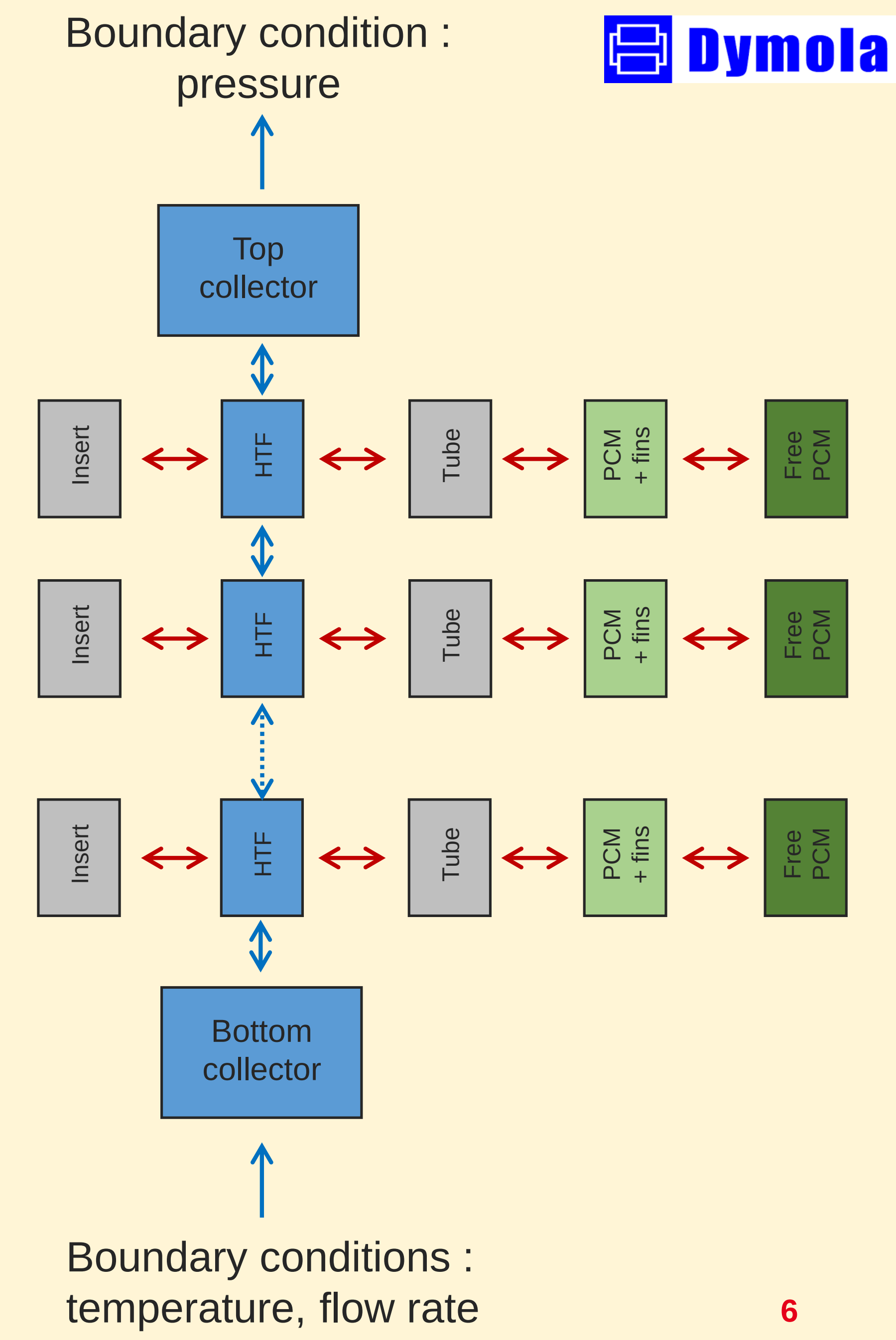
Numerical Model

- **Heat Transfer Fluid**
  - assumed uniformly distributed over the tubes ➔ 2 tubes modeled
  - 1D-axial discretization
  - Enthalpy and mass balance
  - Heat exchange coefficient calculated from classical correlations

- **Insert, tube, fins and PCM**
  - 1D radial discretization
  - Axial conduction neglected
  - Transient heat equation
  - PCM + fins : equivalent material properties

- Model validated on experimental data

(Da Col et al, 2023, doi.org/10.1016/j.est.2023.109239)

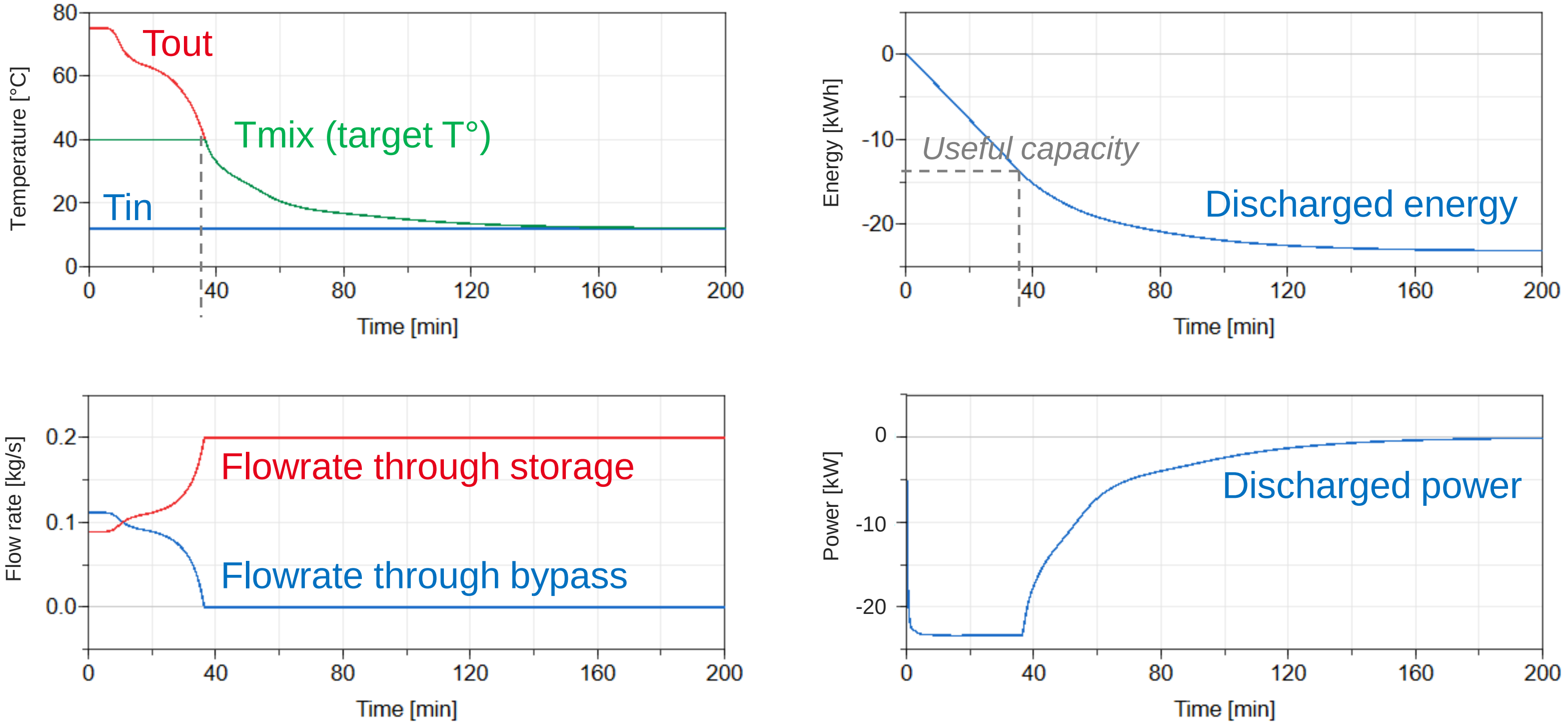


Numerical Model

Inputs :

- TES Design
- TES initial temperature
- HTF temperature and flow-rate at inlet

Results : Evolution with time of various variables



Indicators for our study :

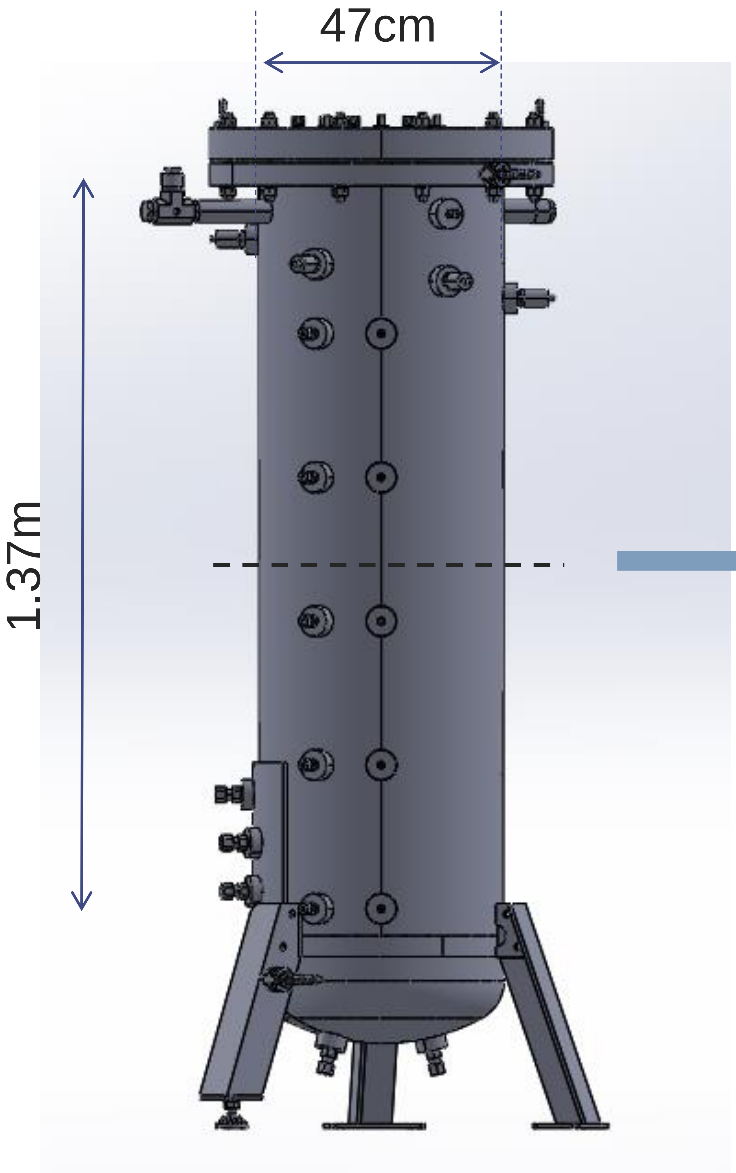
- **Useful capacity** = cumulative energy discharged until the moment when water temperature falls below the target temperature
- **Discharge efficiency** = ratio of useful capacity to energy stored between target and maximum temperature

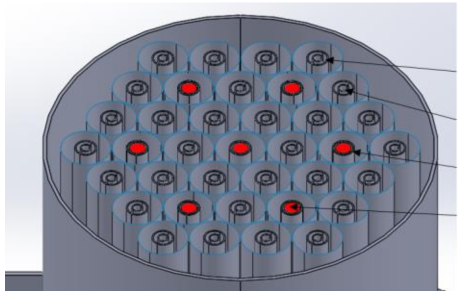
Reference Design

Design

Number of tubes	37
Tube network arrangement	Single pass
PCM	Octadecanol (melting T° 58°C)
Tubes' height	1.37m
Tube path network	67.2mm
Shell diameter	0.47m
Average PCM height	1.27m
PCM mass	146kg

Energy stored betw. 40°C and 75°C	16.2 kWh





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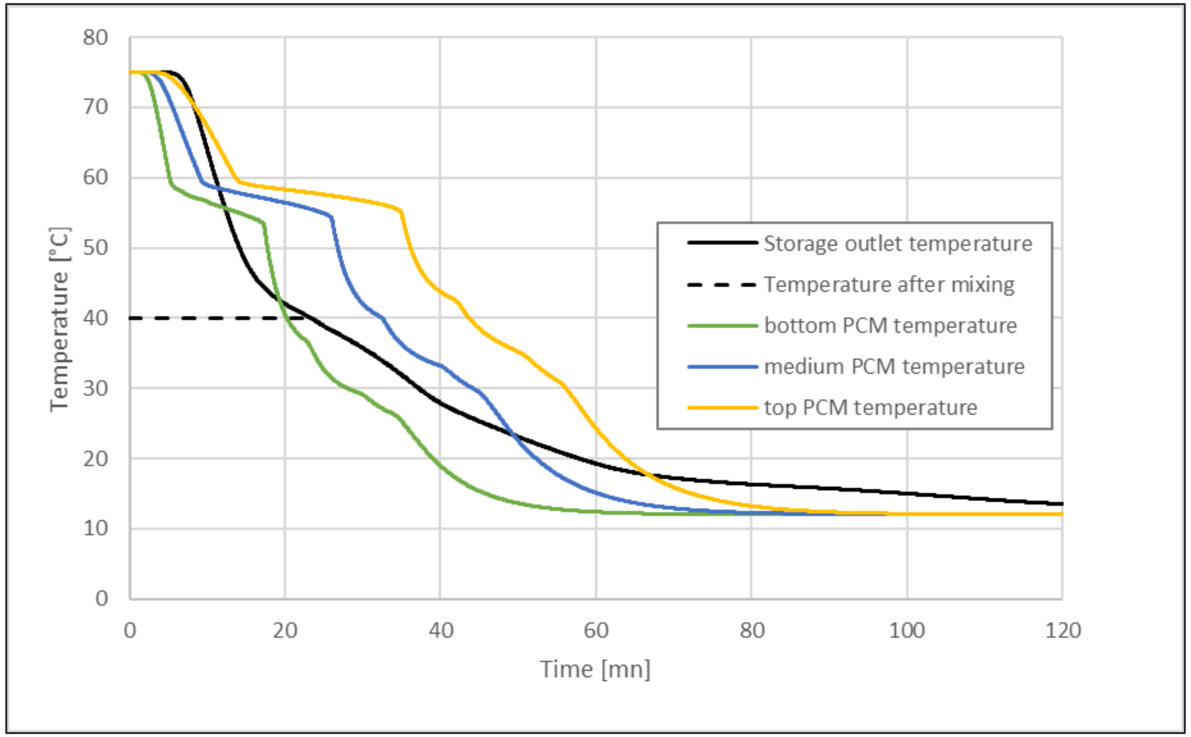
Performance



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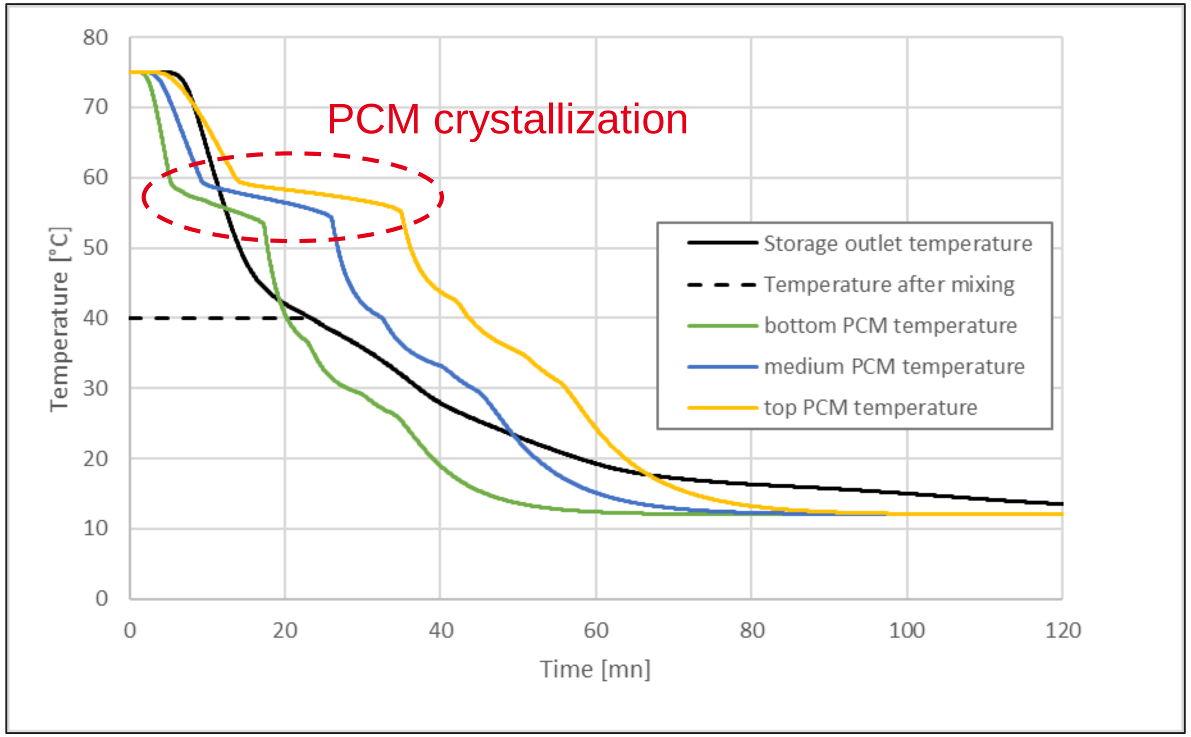

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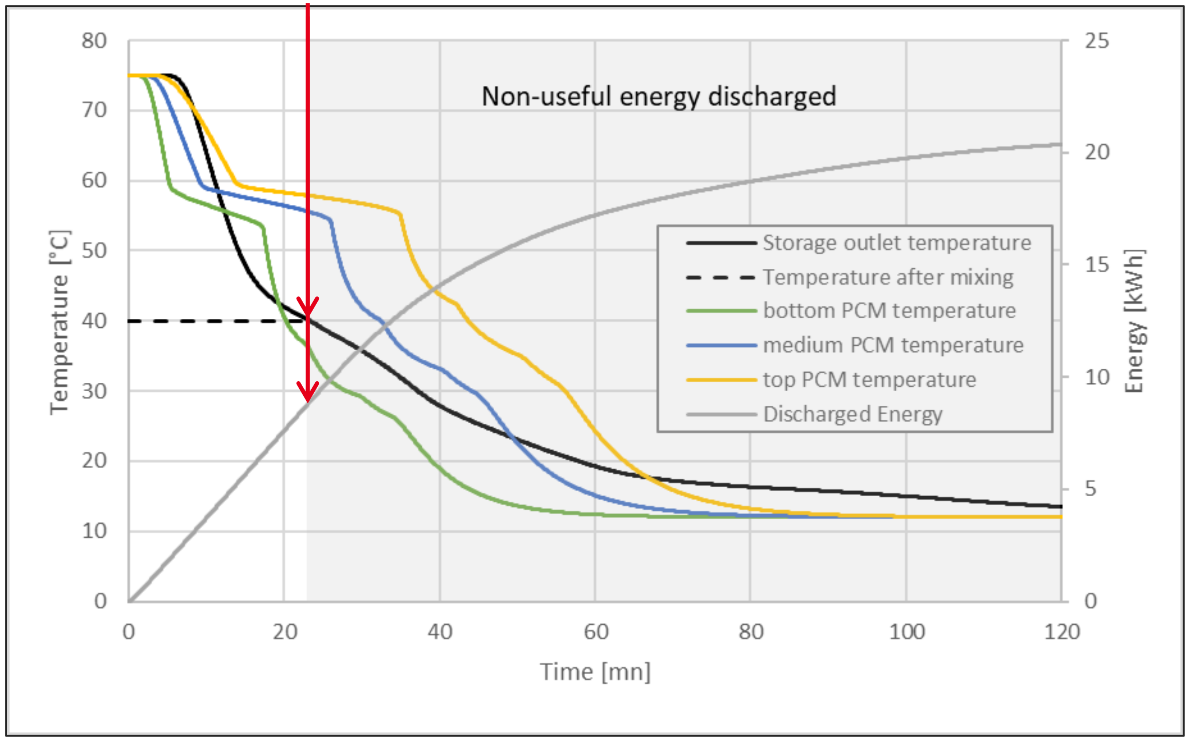
Performance

Storage outlet T° reaches target T°



Useful capacity	8.9 kWh
Discharge efficiency	55%

Impact of PCM

	Bio based PCMs		
	Octadecanol	RT-70 HC	Stearic Acid
Melting temperature	58°C	70°C	70°C
Storage heat capacity (latent + specific heat) in the range [12 – 75]°C	372 kJ/kg	392 kJ/kg	320 kJ/kg
Average density	789 kg/m^3	825 kg/m^3	892 kg/m^3
Storage density	81.5 kWh/m^3	90 kWh/m^3	79 kWh/m^3

- RT-70HC and Stearic Acid have higher melting temperatures than octadecanol
- Better storage heat capacity for RT-70 HC than for Stearic Acid

Impact of PCM

	Octadecanol	RT-70 HC	Stearic Acid
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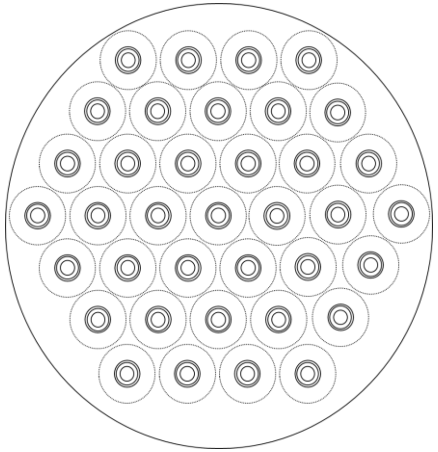
- RT-70HC and Stearic Acid have higher melting temperatures than octadecanol
- Better storage heat capacity for RT-70 HC than for Stearic Acid

PCM	Octadecanol	RT-70 HC	Stearic Acid
PCM Mass [kg]	146	152	165
Energy stored between 40°C and 75°C[kWh]	16.2	17.4	15.4
Useful capacity [kWh]	8.9	12.3 (+38%)	11.0 (+24%)
Discharge efficiency	55%	71%	71%

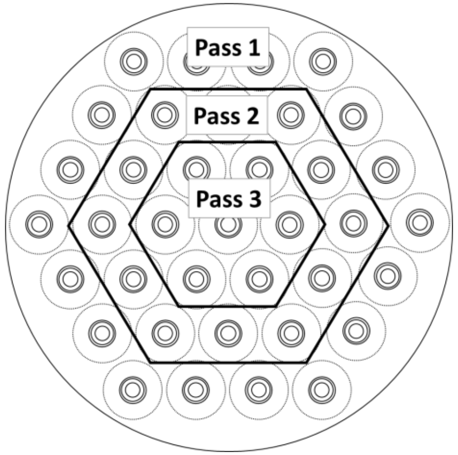
- **Increase in Useful capacity** if RT-70 HC or Stearic Acid is used
- **Explaination**
  - Higher ΔT between PCM and HTF ➔ improved heat exchange
  - Higher melting T° ➔ energy retrieved at higher T°

Impact of tube network arrangement

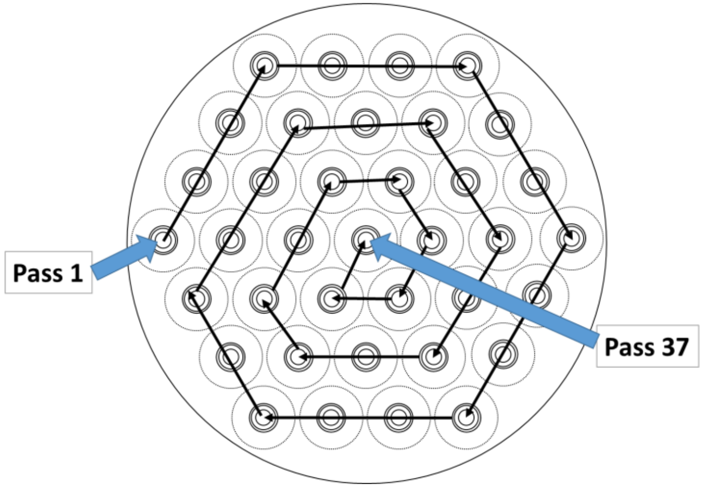
Single-pass



Three-pass

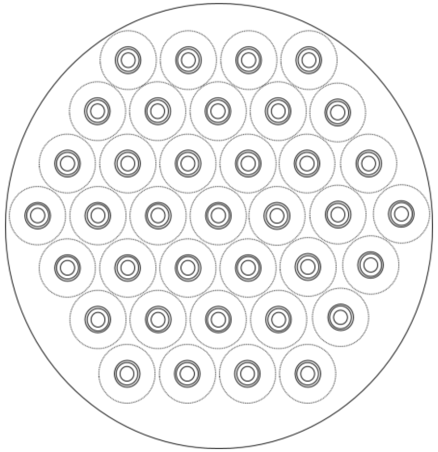


37-pass

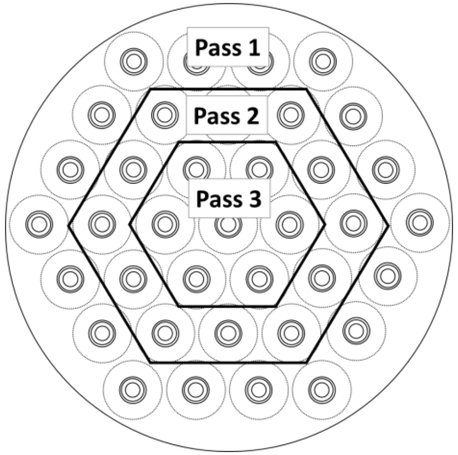


Impact of tube network arrangement

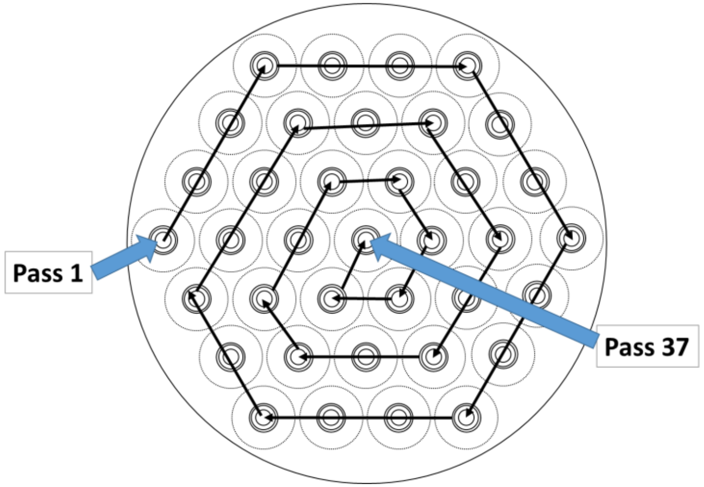
Single-pass



Three-pass



37-pass



Tube network arrangement	Single pass	3-pass	37-pass
PCM Mass	146 kg (octadecanol)		
Energy stored betw. 40°C and 75°C	16.2 kWh		
Useful capacity	8.9 kWh	12.4 kWh (+39%)	16.5 kWh (+85%)
Discharge efficiency	55%	77%	102%

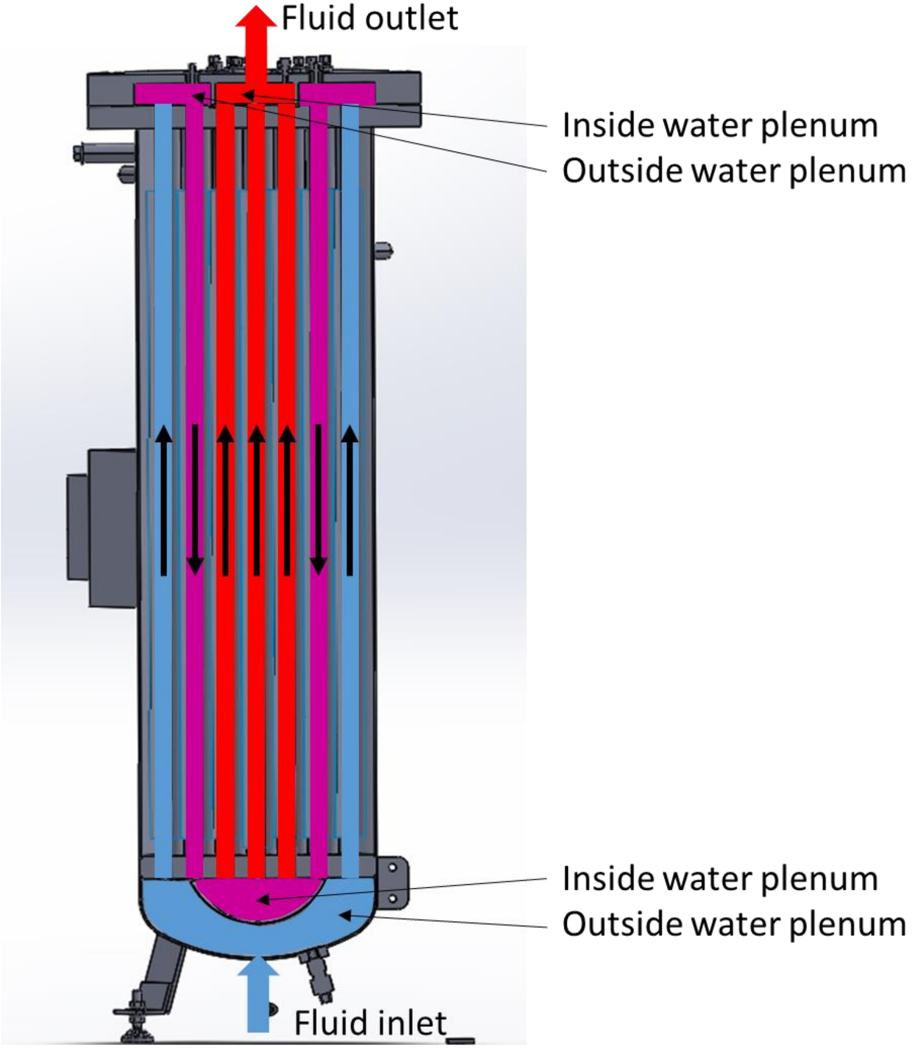
- **Increase in Useful capacity** by re-arranging fluid flow inside tube network
- **Explanation :**
  - increased HTF velocity in the tubes ➔ improved heat exchange

Optimal Design

Design

	Reference	Optimal
Tube network arrangement	Single pass	Three-pass
PCM	Octadecanol	RT-70 HC
PCM mass	146kg	152kg

Energy stored betw. 40°C and 75°C	16.2 kWh	17.4 kWh



Optimal Design

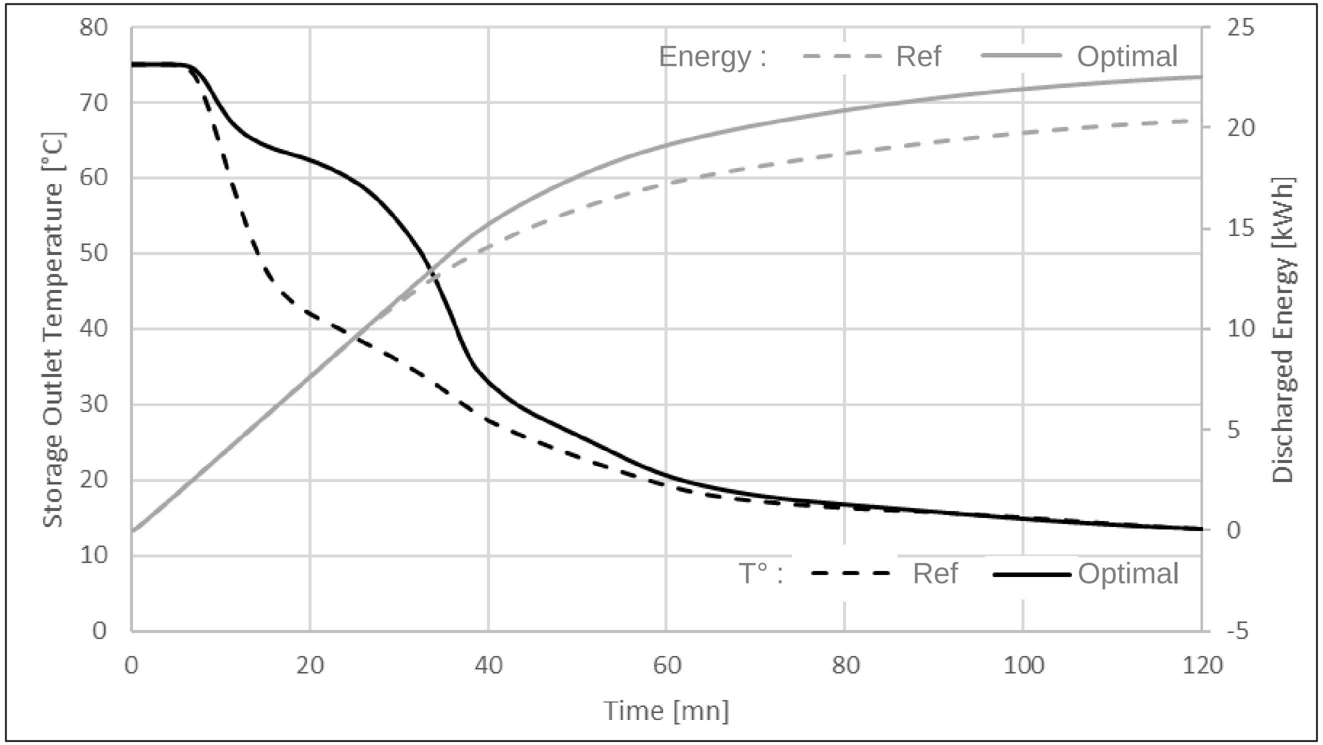
Design

	Reference	Optimal
Tube network arrangement	Single pass	Three-pass
PCM	Octadecanol	RT-70 HC
PCM mass	146kg	152kg

Energy stored betw. 40°C and 75°C	16.2 kWh	17.4 kWh

Useful Capacity	8.9 kWh	14.0 kWh
Discharge Efficiency	55%	80%

Performance



- **Increase in Useful capacity** and **Discharge Efficiency** for the Optimal Design

Conclusion

- In **DHW applications**, only the energy retrieved above a given temperature (depending on the user) is useful

  ➔ Only part of the stored energy is useful

- How can we increase **Useful Storage Capacity**?

  1. **Increase the energy stored in the TES** (by increasing PCM quantity or using a PCM with optimized thermophysical properties)
  2. **Increase the share** of stored energy that can be retrieved above a given temperature level

- Our study shows that it is possible to increase the Useful Storage Capacity by :
  - Choosing a **PCM with a high melting temperature**
  - Arranging the hydraulic circuit in the heat exchanger in **several passes**

Any question?

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Numerical Model

- **Insert, tube, fins and PCM : Transient heat equation**

$$\rho\, Cp\, \frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(\lambda\, r\, \frac{\partial T}{\partial r}\right)$$

ρ, Cp, λ : material properties defined as a function of T for each zone

- PCM : Cp integrates latent heat of fusion
- « PCM + fins » : equivalent material, properties calculated as a function of mass fraction, except for λ

- **Heat Transfer Fluid : Mass balance + enthalpy balance**

$$\frac{\partial(\rho V)}{\partial z} + \frac{\partial \rho}{\partial t} = 0$$

$$S\frac{\partial h}{\partial t} + \frac{\partial(\dot{m}Cp\, T)}{\partial z} = \alpha\, hp\, \Delta T_{HTF,wall}$$

α : heat exchange coefficient, calculated from classical correlations

- HTF is assumed to be uniformly distributed over the tubes

  - Model validated on experimental data

(*Da Col et al, 2023, doi.org/10.1016/j.est.2023.109239)*