7th International Conference on Smart Energy Systems
21-22 September 2021
#SESAAU2021

Realization and energy assessment algorythm of a Horizontal Packed Bed Regenerator for Thermal Energy Storage

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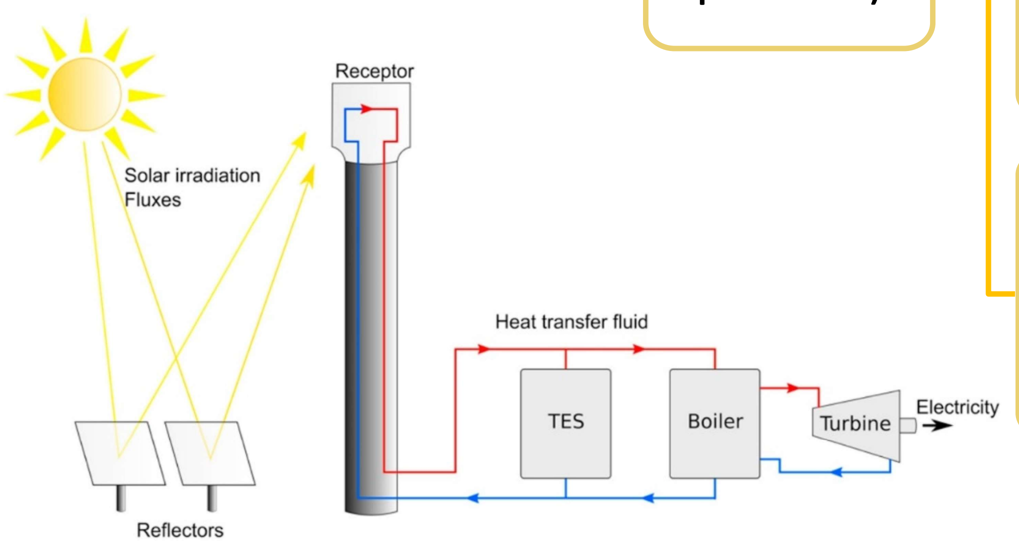
Introduction to TES technology: Overview

Purpose
- Store heat

Scope
- Provide heat to utilities in different conditions (from production)

Applications
- **Industry**
  - CSP Plants
  - Cogeneration
  - Heat regeneration from industrial processes
- **Domestic Use**
  - Buildings cooling
  - Buildings heating

Benefits
- Energy efficiency
- Economy
- Environmental Sustainability
- Availability and Reliability



Introduction to TES technology: Classification

Basic Criterion

Heat Trasfer Fluid (HTF)

- Direct → HTF serves as thermal vector and storage material
- Indirect → HTF exchanges heat with a different medium (storage material)

Heat transfer

- Active → forced heat convection
- Passive → mainly conduction

Operative phases thermody-namics

- Sensible TES→ Temperature gradient
- Latent TES → Phase change
- Thermochemical TES → Chemical reaction

Introduction to TES technology : TES R&D topics for power generation

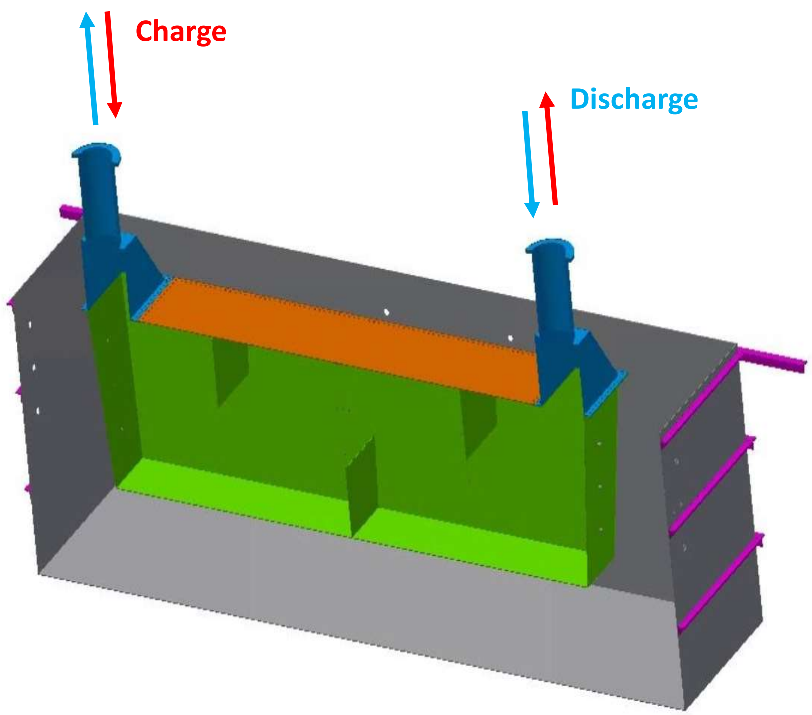
Table 4: Main objectives for technological innovation of TES with CSP

Attribute	Sensible			Latent			Thermochemical		
	2018	2030	2050	2018	2030	2050	2018	2030	2050
Cost (USD/kWh)	25-30	< 15	< 12	25-90	25-35	< 12	Research level	Pilot scale, 80-160	Demon-stration, <80
Efficiency (%)	>90	>92	>95	>90	>92	>95	40-50	(1)	
Energy density (kWh/m³)	70-200	(2)		30-85			800-1200		
Lifetime (years or cycles)	< 10 000	> 10 000		3 000-5 000	4 000-5 000	5 000-10 000	< 100	500-1 000	> 1 000-3 000
Working temperature (°C)	< 565	600-700	> 700	< 600	600-750	700-850	500-900		500-1 000

Notes: (1) Value not available due to low technology readiness level; (2) Value dependent on the material selection.

Source: ***Innovation Outlook – Thermal Energy Storage; IRENA; 2020***

TU Wien Test Rig: Description



Shape → Truncated rectangular based pyramid

Volume → 3.313 m^3

- HTF → Air
- Storage material → Natural gravel

Classification

Active

Indirect

Sensible

TU Wien Test Rig: Materials

Storage Material

- **Natural gravel provided by ASAMER Company**
- **Thermophysical properties not available** → **Needed to be assumed:**
  - ✓ **Density** → **1800** $\frac{kg}{m^3}$
  - ✓ **Specific heat** → **1170** $\frac{J}{kg\ K}$

Steel S235JR

Geocell RED

- **Expanded glass gravel provided by Geocell Schaumglas Company**
- **Structural integrity and insulation efficiency** → **Experimental assessment**

Energy assessment algorythms: Performed analysis

Energy Analysis	Exergy Analysis	Dimensional Analysis

Energy Analysis

- Evaluation of test rig capability to store heat
- Evaluation of **thermal hysteresis effects**

Exergy Analysis

- Evaluation of the thermodynamic quality of the processes occurring during operative phases

Dimensional Analysis

- Evaluation of the relationship between efficiencies and dimensional parameters
- Non-dimensional formulation allows to **extend the validity of energy and exergy analysis to similar systems**

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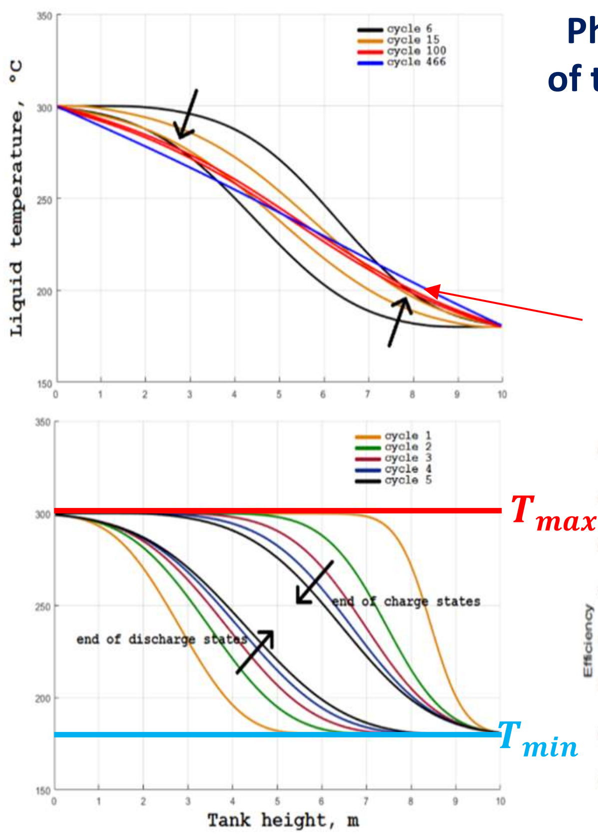
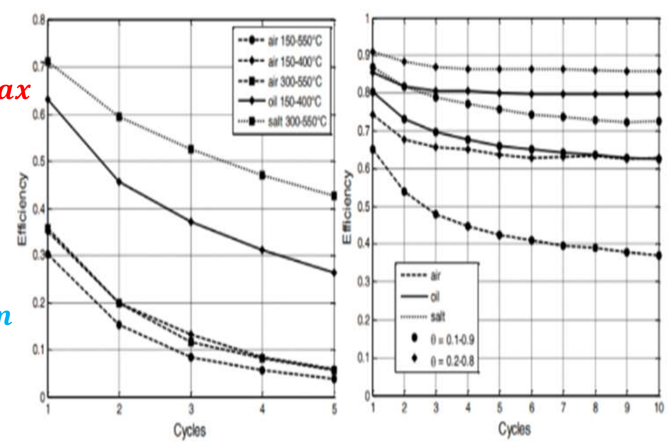
Energy assessment algorythms: Thermal hysteresis



Phenomenon of progressive enlargment of the thermocline thickness (temperature gradient) of storage material with performed cycles → System energy storage capability reduction

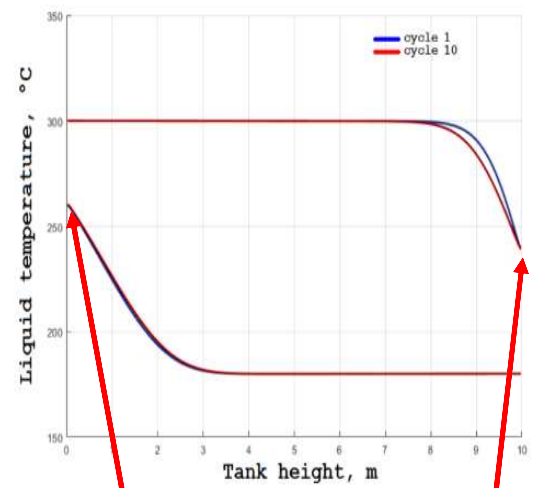
After a finite number of cycles, the system is no more capable to store heat



SOLUTION:

Temperature criteria

$$\theta^{c/d}_{out,end} = \frac{T^{c/d}_{out,end} - T_{min}}{T_{max} - T_{min}}$$



$$T^{c/d}_{out,end} = T_{min} + \theta^{c/d}_{out,end} \Delta T_{max}$$

Energy assessment algorythms: Energy and Exergy analysis algorythms

Storage material energy and entropy

$$U_1 - U_2 = \rho_s c_{v,s} \int_V \left(\widetilde{T}_1(\overline{x}) - \widetilde{T}_2(\overline{x})\right) dV$$

$$S_1 - S_2 = \rho_s c_{v,s} \int_V \ln\left(\frac{\widetilde{T}_1(\overline{x})}{\widetilde{T}_2(\overline{x})}\right) dV$$

- **Perfect incompressible behaviour ($c_{v,s} = c_{p,s}$)**
- **Properties assumed constant within the interval [T_{min}; T_{max}]**

Air (HTF) energy and entropy

$$E_0 - E_{end} = \int_{\tau_{c/d}} \dot{m}_{air}(h_0 - h_{end})_{c/d}\, dt$$

$$S_0 - S_{end} = \int_{\tau_{c/d}} \dot{m}_{air}(s_{end} - s_0)_{c/d}\, dt$$

- **Numerical computation**

Integrals computed with two different methods

- **Volumes Method**
- **Analytical Model**

Energy assessment algorythms: Energy and Exergy analysis algorythms

Volumes Method

hp: 30 volumes (1 for every thermoresistance applied)
Approximated regenerator volume
Homogeneous temperature within each volume

$$U_1 - U_2 = \rho_s c_{v,s} \sum_1^{30} V_i \, (T_1 - T_2)_i$$

$$S_1 - S_2 = \rho_s c_{v,s} \sum_1^{30} V_i \ln\left(\frac{T_1}{T_2}\right)_i$$

Analytical Model

hp: Neglected temperature gradient along z-coordinate
Approximated temperature gradient along y-coordinate
Approximated regenerator volume

$$\tilde{T}(\bar{x}) = \tilde{T}(x,y,z) = \tilde{T}(x,y) \approx \tilde{T}(x)$$

$$U_1 - U_2 = \rho_s c_{v,s} \Omega \int_0^L \left(\tilde{T}_1(x) - \tilde{T}_2(x)\right) dx$$

$$S_1 - S_2 = \rho_s c_{v,s} \Omega \int_0^L \ln\left(\frac{\tilde{T}_1(x)}{\tilde{T}_2(x)}\right) dx$$

Energy assessment algorythms: Dimensional analysis

	Quantity	Unit
Operational Parameters	T_H	K
	T_C	K
	$T^c_{f,out,end}$	K
	$T^d_{f,out,end}$	K
	$\dot{m}"_f$	kg/m^2s
	Δt_c	s
	Δt_d	s
	n	-
Geometrical Parameters	L	m
	d	m
	H	m
	W	m
	$\tan\alpha$	-
	ϵ	-
HTF Thermophysical Properties	$c_{p,f}$	J/kg K
	$c_{v,f}$	J/kg K
	ρ_f	kg/m^3
	k_f	W/m K
	μ_f	Pa s
Storage material Thermophysical Properties	$c_{p,s}$	J/kg k
	ρ_s	kg/m^3
	k_s	W/m K

	Quantity	Π
Operational Π	T_C	$\Pi_{T_C} = \frac{T_C}{T_H}$
	$T^c_{f,out,end}$	$\Pi_{T^c_{f,out,end}} = \frac{T^c_{f,out,end}}{T_H}$
	$T^d_{f,out,end}$	$\Pi_{T^d_{f,out,end}} = \frac{T^d_{f,out,end}}{T_H}$
	Δt_c	$\Pi_{\Delta t_c} = \frac{\dot{m}''_f}{L\ \rho_s} \cdot \Delta t_c$
	Δt_d	$\Pi_{\Delta t_d} = \frac{\dot{m}''_f}{L\ \rho_s} \cdot \Delta t_d$
	n	$\Pi_n = n$
Geometrical Π	d	$\Pi_d = \frac{d}{L}$
	H	$\Pi_H = \frac{H}{L}$
	W	$\Pi_W = \frac{W}{L}$
	$\tan\alpha$	$\Pi_\alpha = \tan\alpha$
	ϵ	$\Pi_\epsilon = \epsilon$
HTF Thermophysical Π	$c_{p,f}$	$\Pi_{c_{p,f}} = \frac{T_H \cdot \rho_s^2}{(\dot{m}''_f)^2} \cdot c_{p,f}$
	$c_{v,f}$	$\Pi_{c_{v,f}} = \frac{T_H \cdot \rho_s^2}{(\dot{m}''_f)^2} \cdot c_{v,f}$
	ρ_f	$\Pi_{\rho_f} = \frac{\rho_f}{\rho_s}$
	k_f	$\Pi_{k_f} = \frac{T_H \cdot \rho_s^2}{L \cdot (\dot{m}''_f)^3} \cdot k_f$
	μ_f	$\Pi_{\mu_f} = \frac{1}{L \cdot (\dot{m}''_f)_f} \cdot \mu_f$
Storage material Thermophysical Π	$c_{p,s}$	$\Pi_{c_{p,s}} = \frac{T_H \cdot \rho_s^2}{(\dot{m}''_f)^2} \cdot c_{p,s}$
	k_s	$\Pi_{k_s} = \frac{T_H \cdot \rho_s^2}{L \cdot (\dot{m}''_f)^3_f} \cdot k_s$

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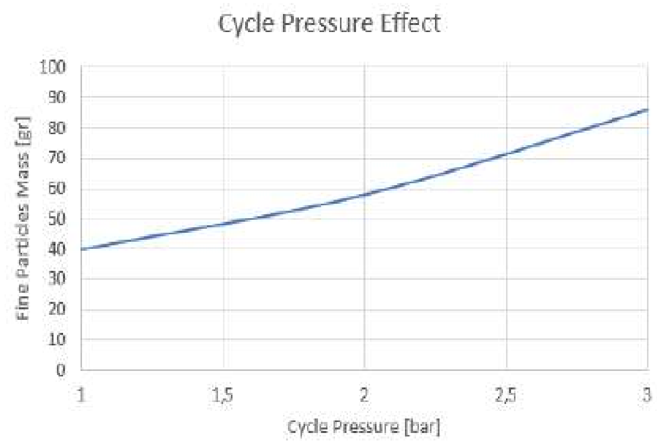
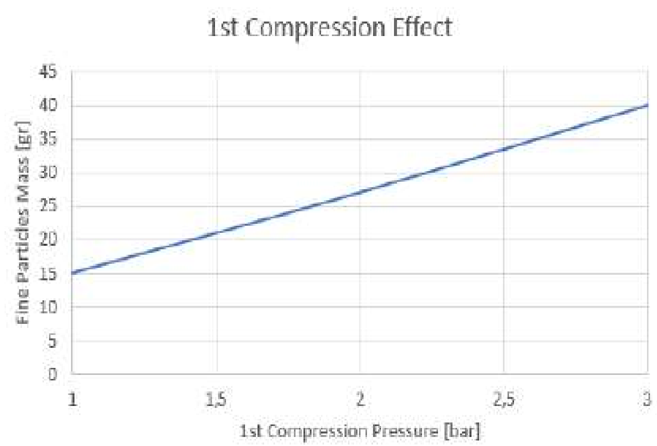
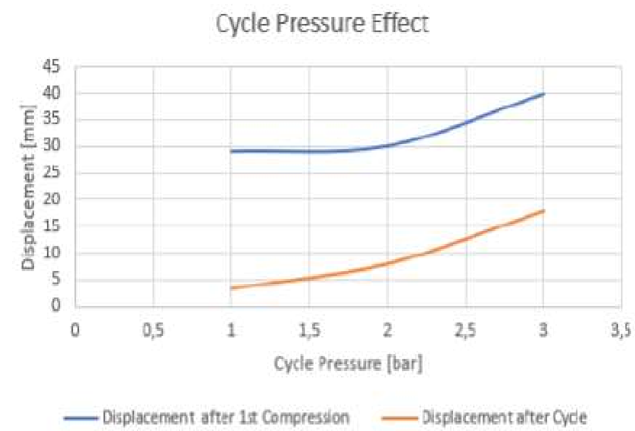
Commissioning activities: Geocell RED Evaluation results

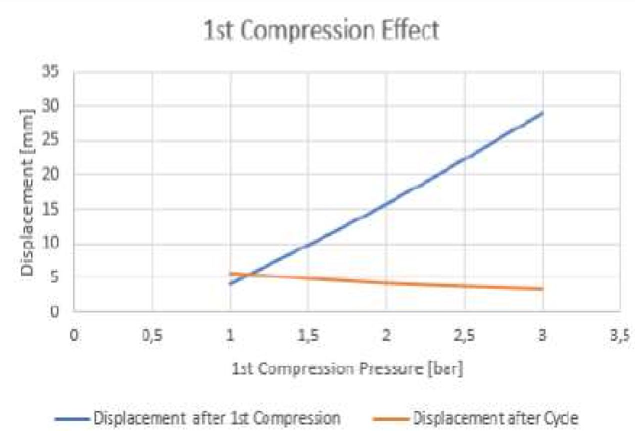
Fine particle mass





Press displacement





Temperature effects

↓

Net increase of fine particle generation (from 2% to 6%) but almost constant press displacement (thermal expansion)

↓

Insulation efficiency decay and structural integrity compromised due to thermal expansion-compression

Insulation efficiency and structural integrity issue

Preliminary test: Description

Parameters

Air mass flow $\dot{m}$	$150\ kg/h$
Charging temperature T_{max}	$85\ °C$
Discharging temperature T_{min}	$30\ °C$
Temperature criterion $\left[\theta^{c}_{out,end}; \theta^{d}_{out,end}\right]$	$[0.1818; 0.5455]$
Number of performed cycles n	2

Scope: testig the automathic mode of the control system

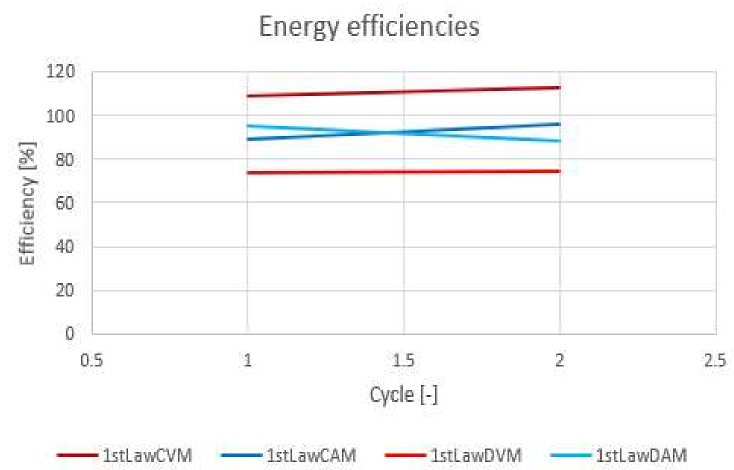
Parameters settled to have fast cycles

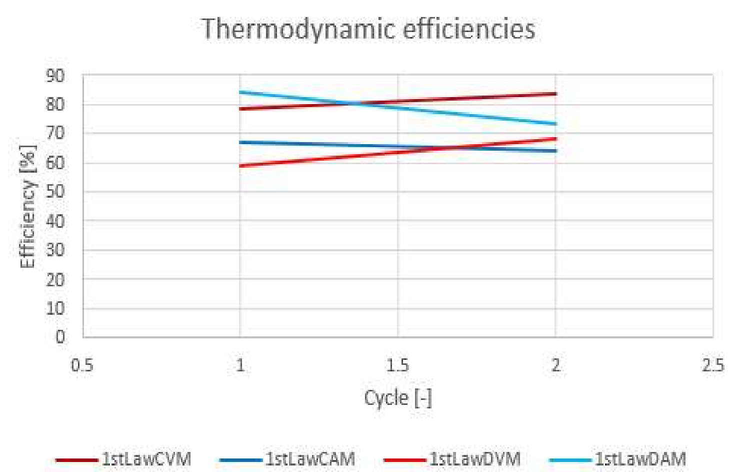
Preliminary test: Energy and Exergy analysis

VM	1st law efficiency	2nd law efficiency
C1	108.86%	78.76%
D1	73.49%	58.74%
C2	112.76%	83.44%
D2	74.61%	63.38%

AM	1st law efficiency	2nd law efficiency
C1	89.02%	67.07%
D1	94.89%	84.29%
C2	96.04%	63.94%
D2	88.04%	73.05%

Volumes Method
Analytical Model

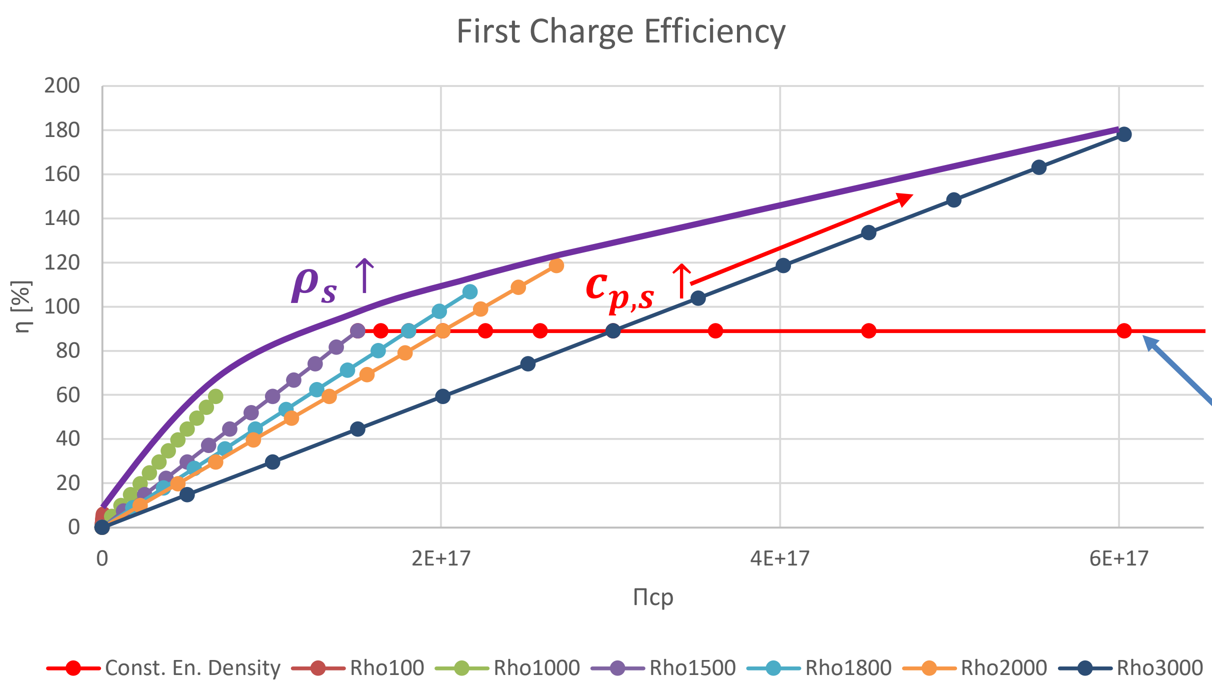




Preliminary test: Dimensional analysis

Assessment of the response of the Analytical Model to changes in storage material density and specific heat assumptions →

$$\Pi_{c_{p,s}} = \frac{T_{max}\rho_s^2 L^2}{\dot{m}^2} c_{p,s}$$



$$E_s^{\leftrightarrows} \propto V_s c_{p,s} \rho_s \Delta T \propto c_{p,s} \rho_s$$

$$\eta_c \propto E_s^{\leftarrow}$$

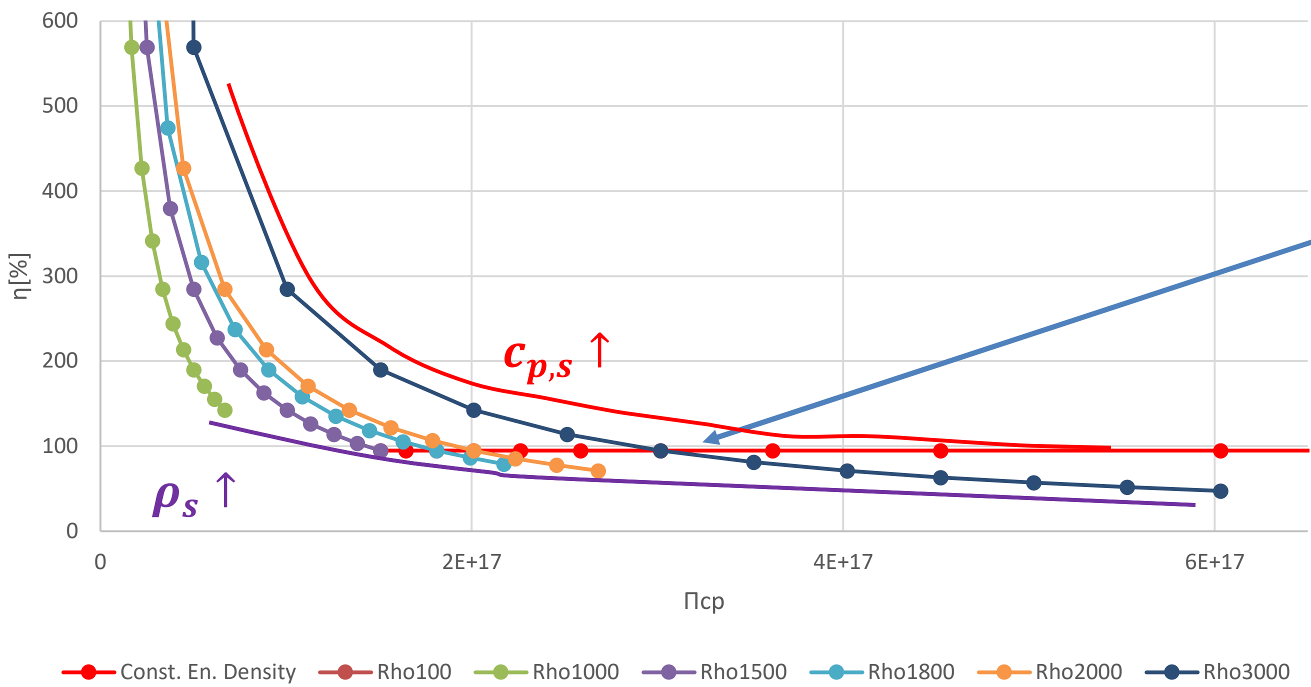
Constant energy density

Preliminary test: Dimensional analysis

$$\Pi_{c_{p,s}} = \frac{T_{max}\rho_s^2 L^2}{\dot{m}^2} c_{p,s}$$

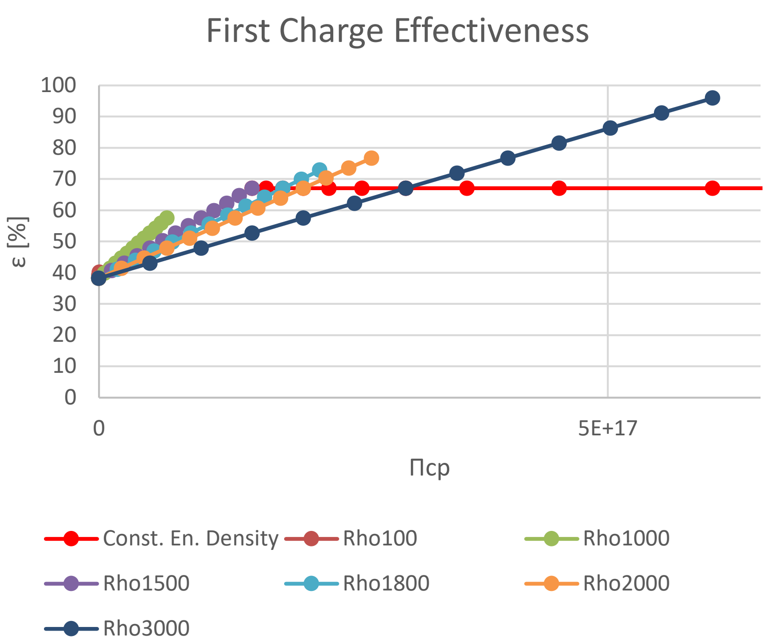
$$\eta_d \propto \frac{1}{E_{\vec{r}}}$$

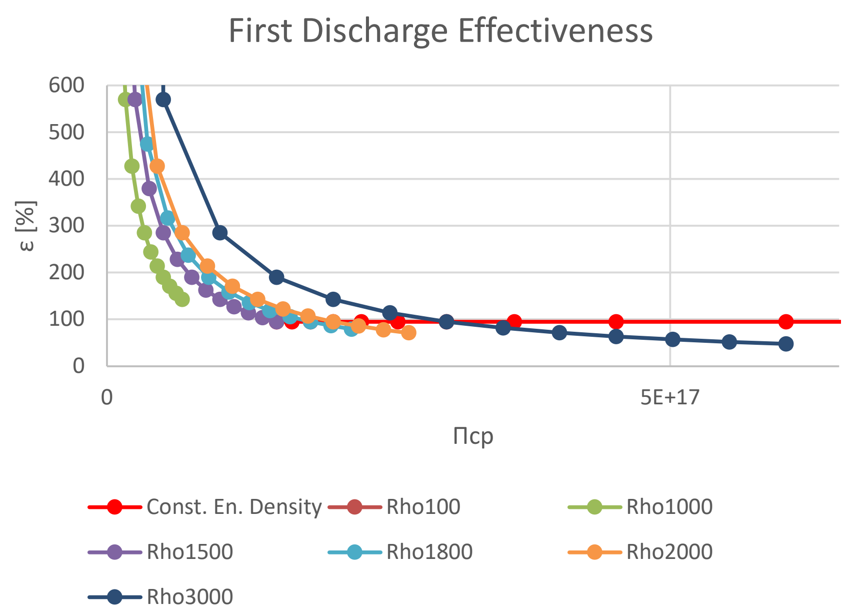
First Discharge Efficiency



Constant energy density

Preliminary test: Dimensional analysis





Conclusions

Energy and Exergy analysis

- **Insufficient accuracy of the VM with provided instrumentation**
- **AM properly describes test rig behaviour**
- **Necessity of a more accurate experimental campaign to assess the validity of both models**

Dimensional Analysis

- **Necessity of storage material thermophysical property knowledge**
- **Useful tool for the design of TES systems**

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