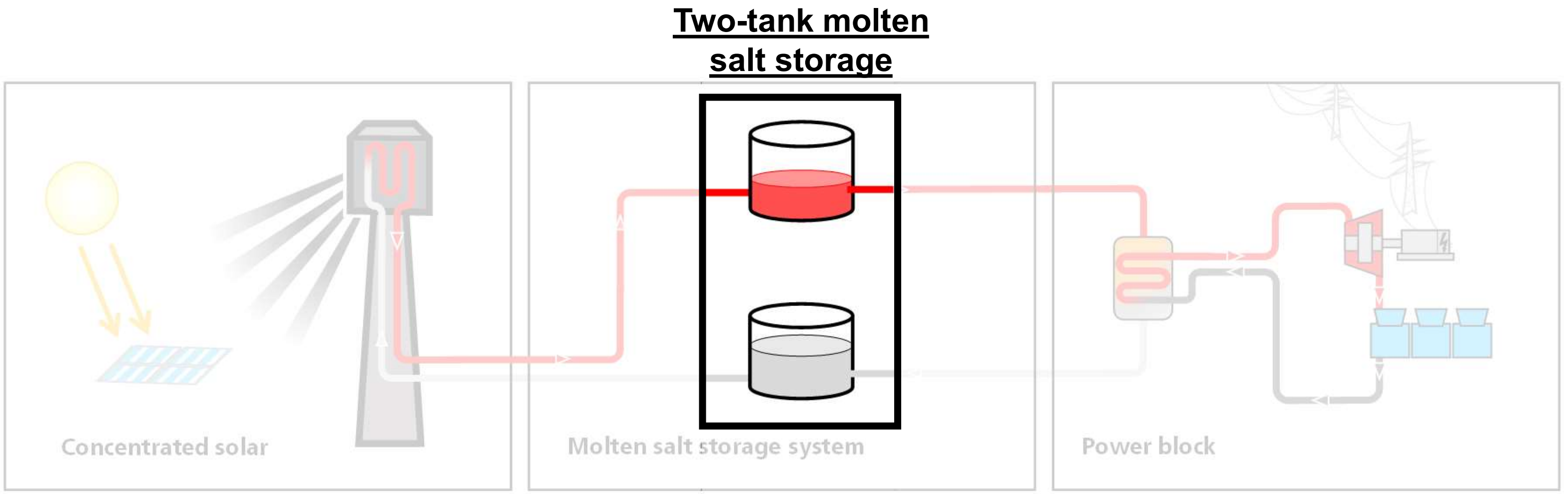
THERMALLY INDUCED TANK STRESS IN A SINGLE TANK

Freerk Klasing[1], Marco Prenzel[1], Christian Odenthal[1] and Thomas Bauer[1]

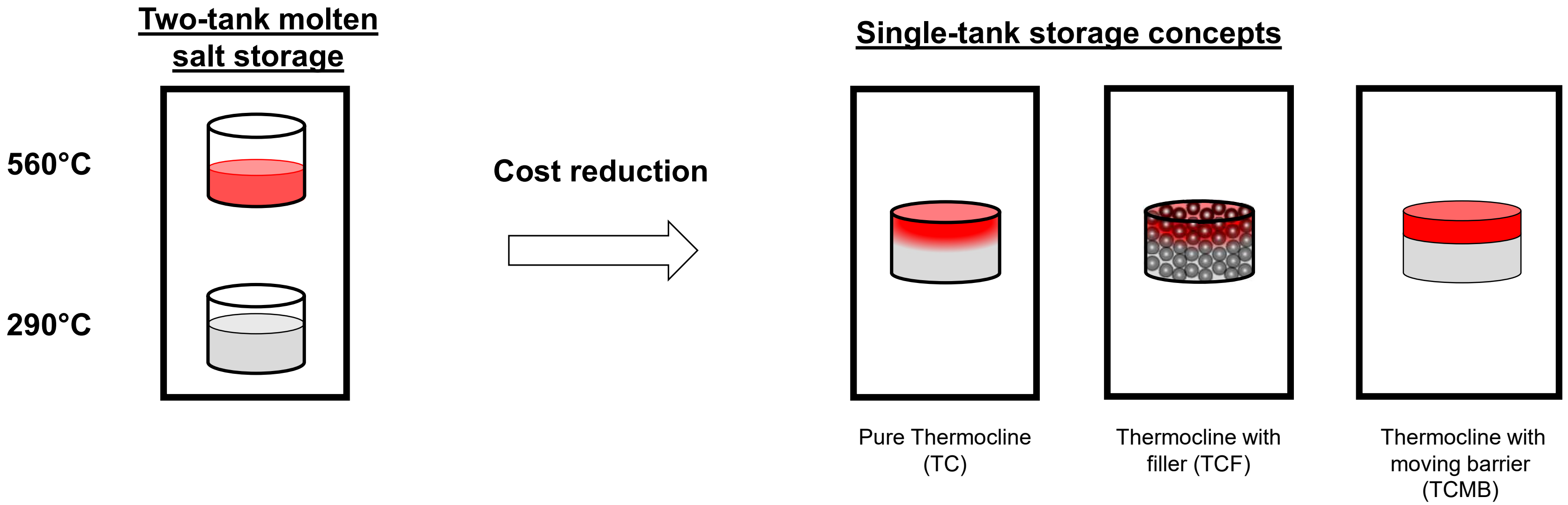
[1] Institute of Engineering Thermodynamics, German Aerospace Center, Cologne

DLR

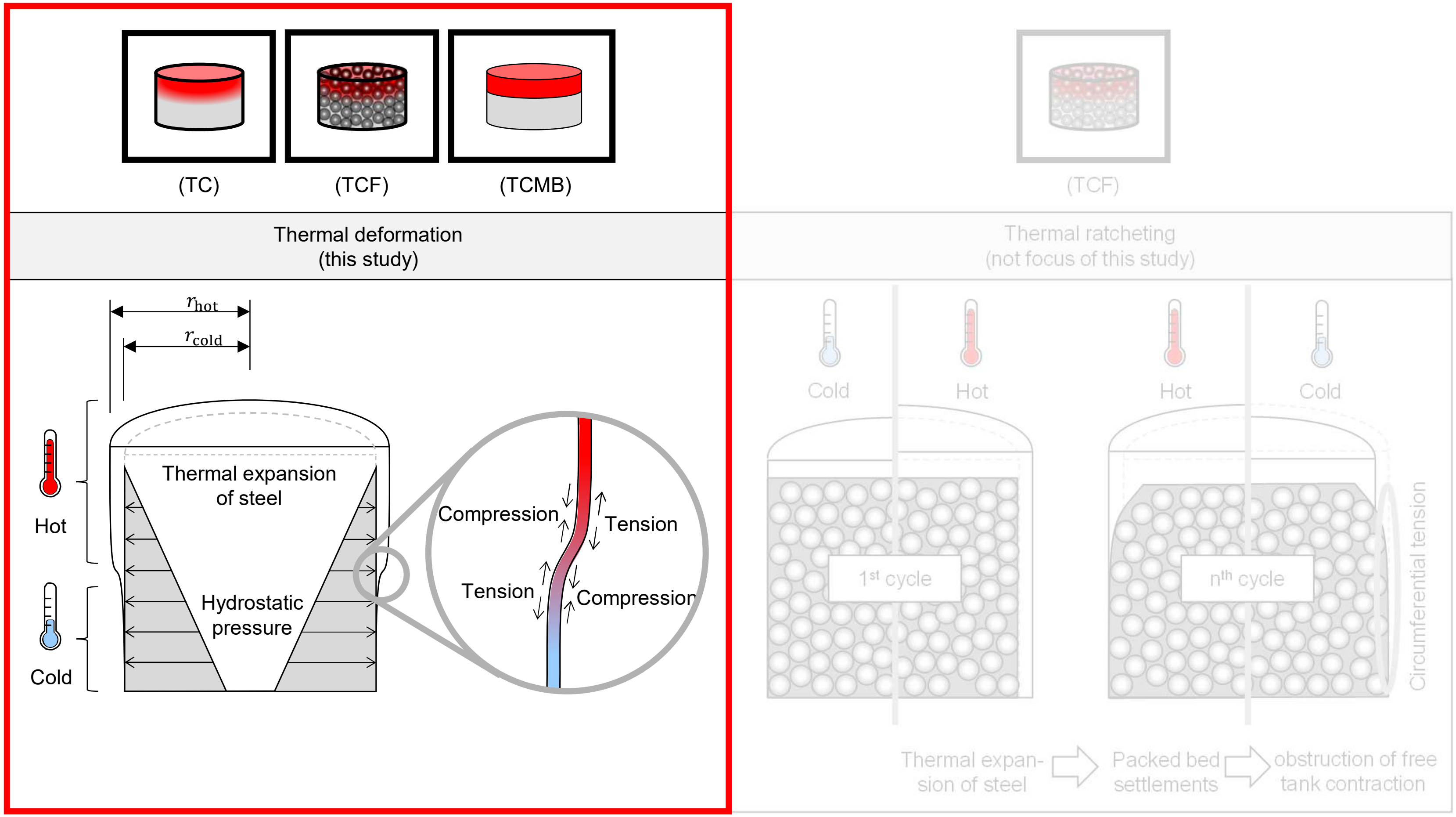
Motivation


Two-tank molten salt storage
Concentrated solar
Molten salt storage system
Power block

Motivation

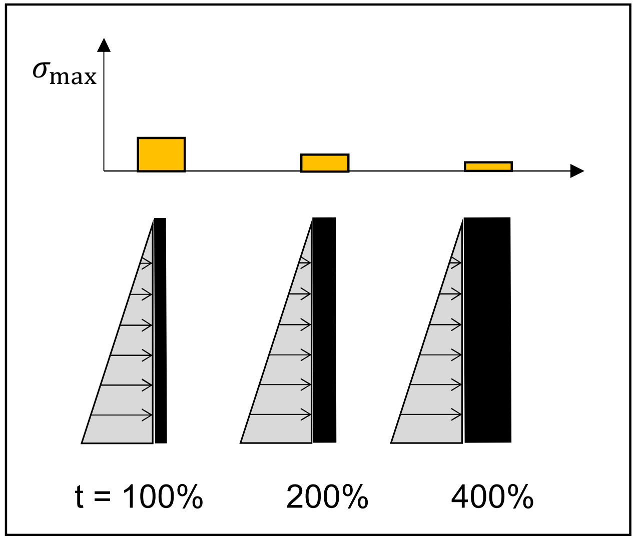

Two-tank molten salt storage
560°C
290°C
Cost reduction
Single-tank storage concepts
Pure Thermocline (TC)
Thermocline with filler (TCF)
Thermocline with moving barrier (TCMB)

Challenge: Single tank at elevated temperatures

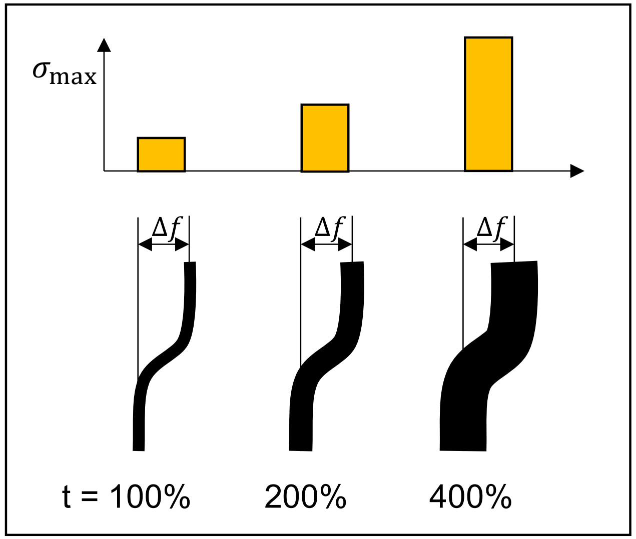


Challenge: Single tank at elevated temperatures

Hydrostatic pressure



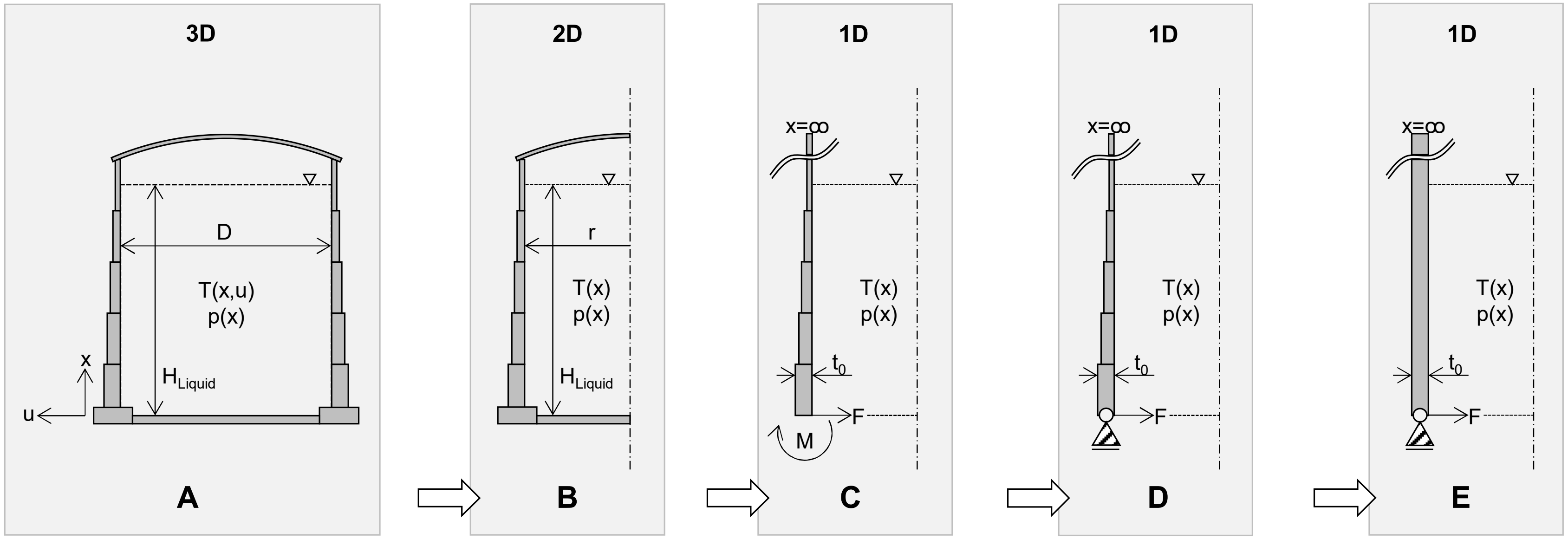
Deformation



- Stress decreases with thicker walls
- Stress increases with thicker walls

How big can a single-tank storage be built?

Methodology
Model development



FEM Analysis

Matlab model

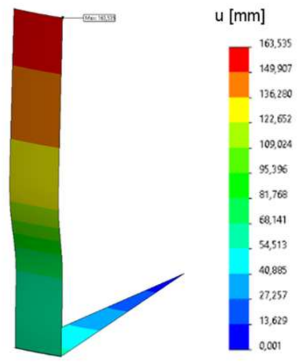
Validation with Faas et a.

Validation with Kang et al.

Parameter variation

Methodology
Model development

- FEM: Rotationally symmetrical "pie slice" of a tank incl. base and roof.
- Matlab: Numerical solution of the 4th order ODE [1] for the rotationally symmetric deformation of a cylinder due to thermal expansion (boundary value problem):



Differential equation

$$\frac{d^2}{dx^2}\left(D\frac{d^2u}{dx^2}\right) + 4 \cdot D \cdot \beta^4 \cdot u = p + \frac{E \cdot t \cdot \alpha}{r} \cdot (T - T_0)$$

- Radial deformation: u
- Bending stiffness: D
- Parameters dependent on transverse contraction coefficient, bending stiffness and tank wall thickness: β
- Inner pressure: p
- Young's-modulus, tank wall thickness, coefficient of expansion: $E \cdot t \cdot \alpha$
- Cylinder radius: r
- Temperature difference relative to origin: $(T - T_0)$

Deformation → **Stress** → **Equivalent stress**

Deformation	Stress	Equivalent stress
$u(x)$	$\sigma_{xb}(x)$, $\sigma_{hm}(x)$, $\sigma_{hb}(x)$	$\sigma_{v'Mises}(x)$

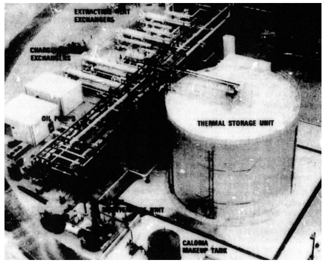
[1] Timoshenko, S. and S. Woinowsky-Krieger, *Theory of Plates and Shells*. 1959: McGraw-Hill.

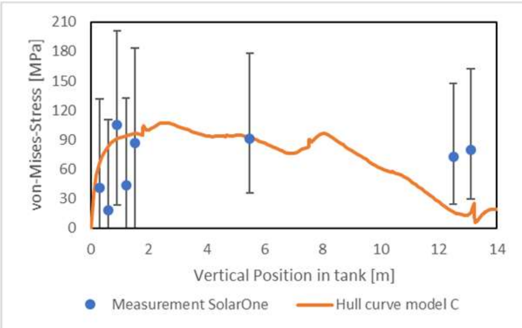
Methodology
Model validation

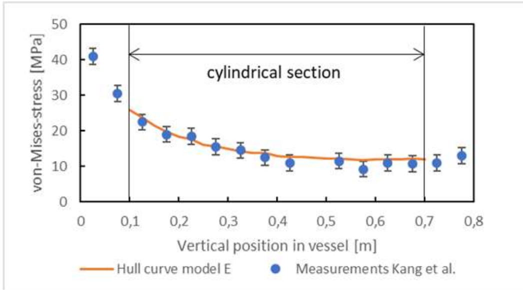
- Validation with 2 Experiments

Thermocline Filler Solar One [2]
(177 °C – 304 °C)
Model D

Kryogenic Tank [3]
(-169 °C – 20 °C)
Model E

[2] 





 [3]

➔ The model reproduces the stresses with sufficient accuracy.

[2] Faas, S.E., et al., 10 MWe Solar Thermal Central Receiver Pilot Plant: Thermal Storage Subsystem Evaluation - Final Report. 1986, Sandia National Laboratories.
[3] Kang, Z., et al., Experimental study on cool down characteristics and thermal stress of cryogenic tank during LN2 filling process. Applied Thermal Engineering, 2018. 130: p. 951-961.

Methodology
Parameter study

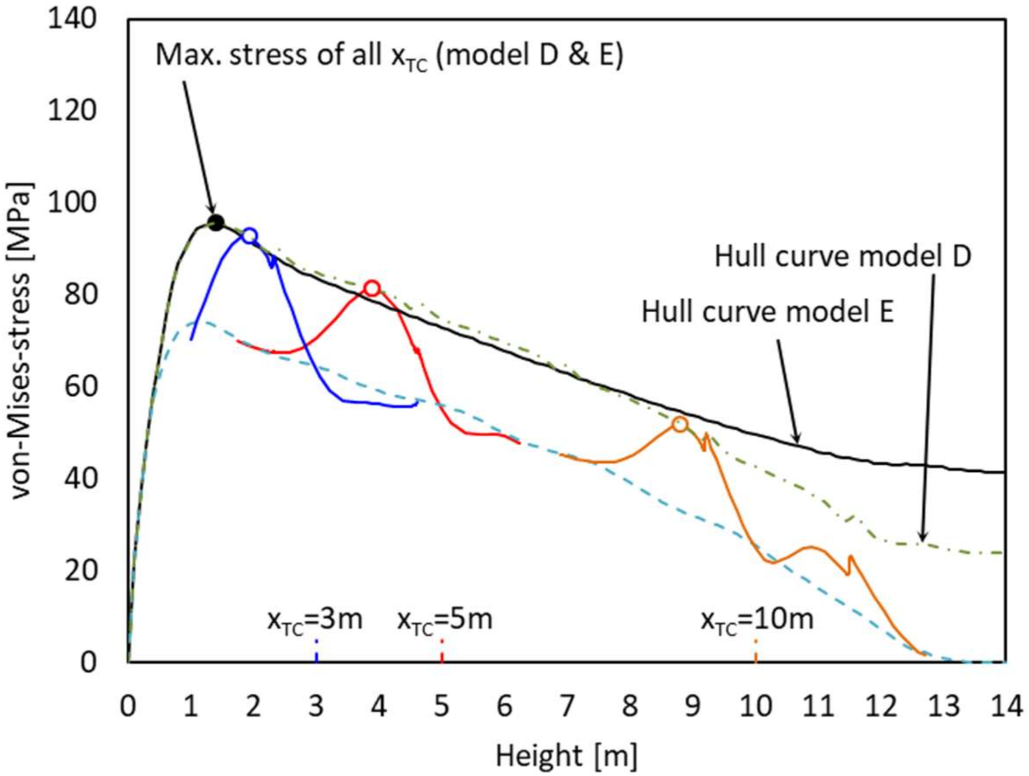
Definition of a simplified temperatrure distribution

Parameter variation matrix:

Position of thermocline x_{TC} Thermocline thickness L_{TC} Temperature difference ΔT Tank diameter D Hydrostatic pressure p_{hyd} Tank wall thickness t

⇩

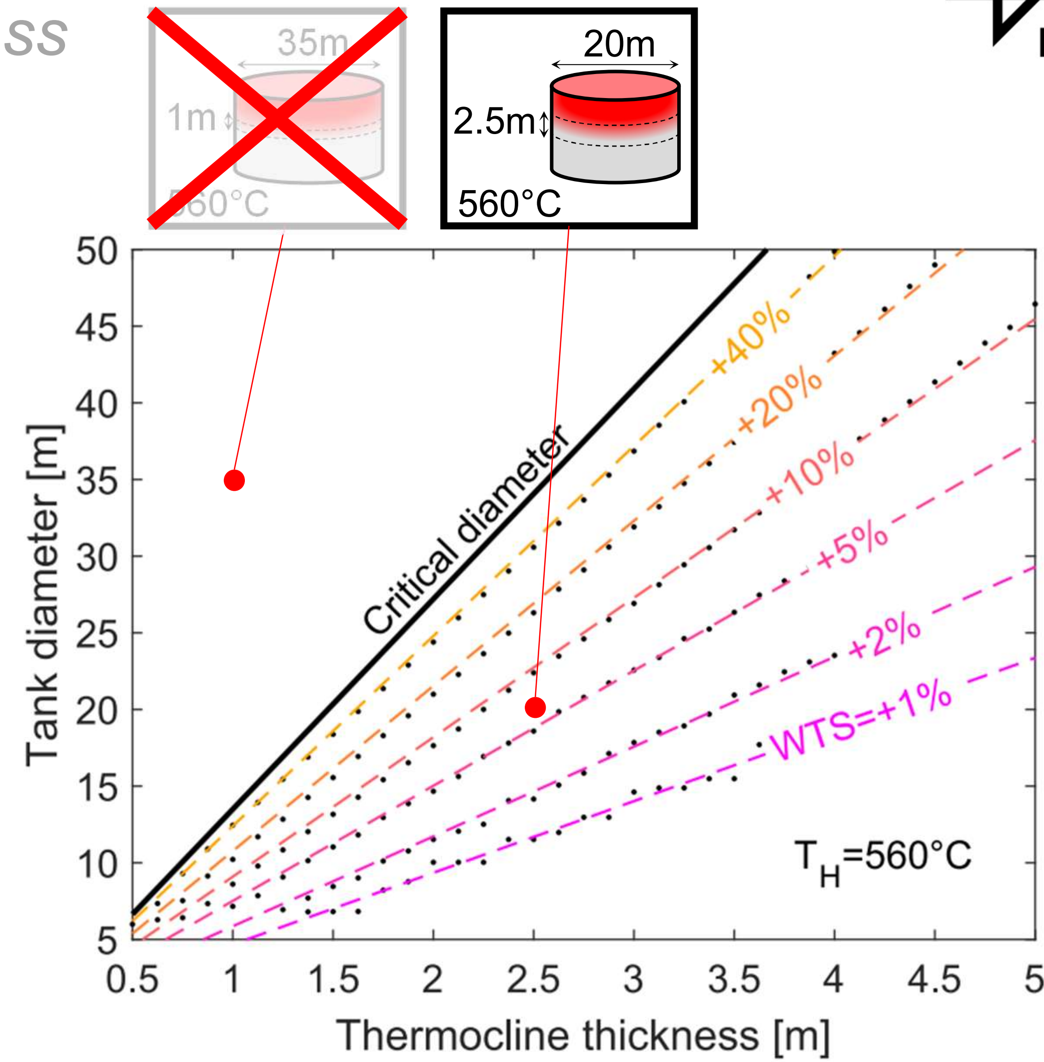
Max stress σ_{max}



Results

Example for 76 MPa design stress

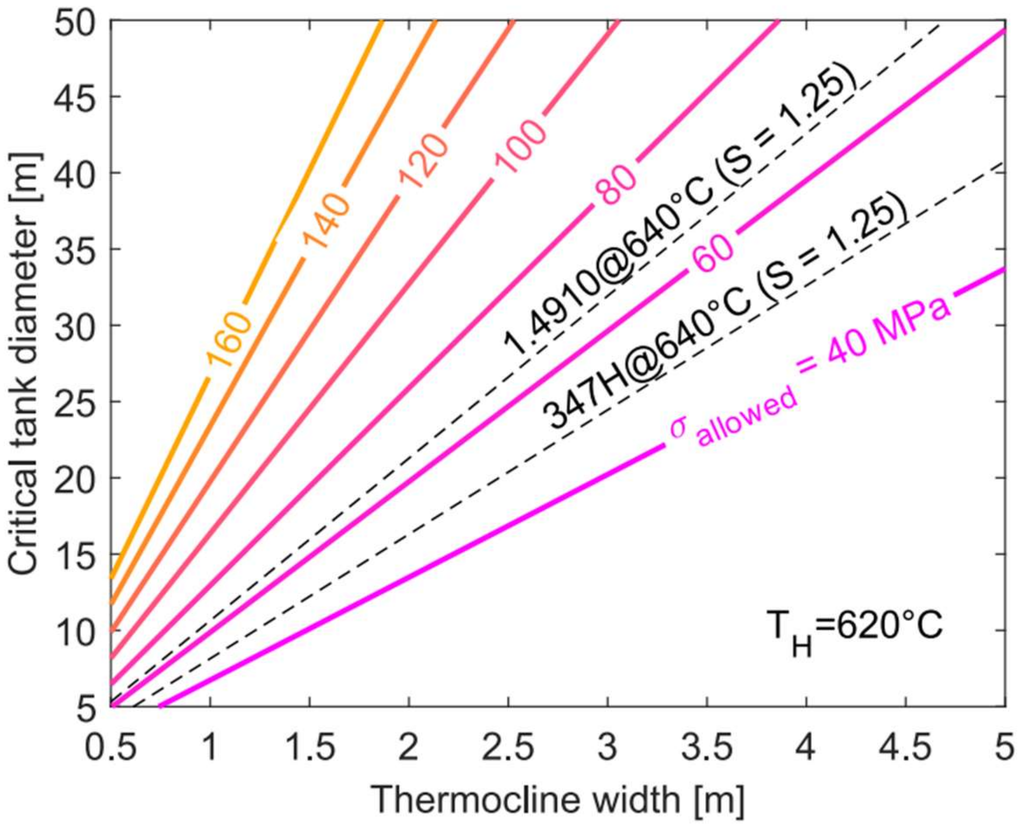
- Critical diameter identified
- Required wall thickness surchage (WTS) increases at an accelerated rate as the critical diameter is approached.



Results
Parameter study

- Critical diameter identified for variations in:
  - Temperature difference ΔT
  - Hydrostatic pressure p_{hyd}
  - Design stress $\sigma_{\mathrm{allowed}}$
- Derivation of a generally applicable formula for the critical diameter:

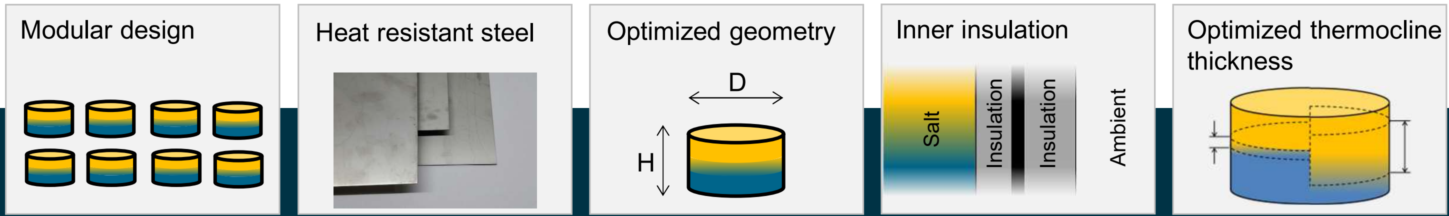
$$\boldsymbol{D}_{\mathbf{critical}} \approx f\left(L_{\mathrm{TC}}; \sigma_{\mathrm{allowed}}; p_{\mathrm{hyd}}; \Delta T\right)$$



Conclusion

- Comprehensive structural mechanical analysis reveals the **general feasibility** of large scale single-tank storage for $D < D_{\mathrm{critical}}$

- Possible design improvements:



Journal of Energy Storage 101 (2024) 113870

Contents lists available at ScienceDirect

Journal of Energy Storage

journal homepage: www.elsevier.com/locate/est

Research papers

Critical diameter for a single-tank molten salt storage – Parametric study on structural tank design

Freerk Klasing [a,*], Mark Schmitz [b], Christian Gerdes [c], Christian Odenthal [a], Thomas Bauer [a]

[a] German Aerospace Center, 51147 Cologne, Germany
[b] TSKFlagsol Engineering GmbH, 50678 Cologne, Germany
[c] JPM Ingenieurtechnik GmbH, 24558 Henstedt-Ulzburg, Germany

ARTICLE INFO

Keywords:
Upscaling
Single-tank
Thermocline
Thermal stress
Molten salt
Thermal energy storage

ABSTRACT

Molten salt thermal energy storage (TES) is a cost-effective option for grid-connected storage in both concentrating solar power (CSP) plants and retrofitted thermal power plants in a multimegawatt scale. Current systems use two tanks (hot and cold), but future systems may use a single tank with a transient temperature profile (hot in the top and cold in the bottom) to reduce costs and space. However, the structural and mechanical design of large-scale molten salt single-tank storages at 560 °C has not been fully explored, and the impact of increasing the operating temperature to 620 °C is still uncertain. The challenge presented by a single tank is the existence of a temperature profile that results in a varying thermal expansion of the tank shell along its height. In the case of larger tanks, this discrepancy can reach a magnitude of centimeters, which in turn gives rise to bending moments. To the best of our knowledge, this study addresses the issue of bending stresses in large-sized high-temperature tanks with thermal stratification for the first time. The modelling approach is applied to single-tank CSP TES systems as a case study to evaluate the constraints imposed by tank size and wall thickness.

With the help of experimentally validated numerical methods, it is revealed that a low thermocline thickness can be a limiting factor for large tank diameters. It is shown that the temperature has a major influence on maximum possible tank size: if the operating temperature is raised from 560 °C to 620 °C, the permitted tank diameter is significantly reduced when using the same tank wall material. A possible approach is to use a more heat resistant steel for 620 °C. Results of the parametric study show that designing a single tank below a critical diameter only requires a moderate increase of the wall thickness compared to the two-tank system with constant temperature profiles. Based on this parametric study a formula for the critical tank diameter is developed and presented in this work. The paper concludes with recommendations on how increased wall stresses can be addressed by an appropriate design.

1. Introduction

High temperature thermal energy storage (TES) is a key element of

worldwide as of today [4]. Besides its use in CSP, molten salt storage is proposed for the use in conventional thermal power plants as well [5–10]. Molten salt thermal energy storage represents an exceptionally

DLR

Paper available here:
10.1016/j.est.2024.113870

Contact:
freerk.klasing@dlr.de