CFD-Based Design and Characterization of Hot Water Seasonal Heat Stores

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Points of Discussion

• New method of characterization of thermal energy stores (TES)

• Novel definition for TES efficiency

• Sample analysis of the charging/discharging process of hot water seasonal heat stores (HWSHS)

• Sample analysis of the storing process of HWSHS

• General procedure for HWSHS design analysis
Types of TES Characterization

• Based on dimensionless numbers
  – insightful but non-comprehensive

• Based on the First Law
  – neglect of the mixing effects

• Based on the Second Law
  – disregard for energy extraction efficiency
New Approach to TES Characterization

- Suitable characterization of TES has to integrate First and Second Law concerns
  - the First Law concern
    - Energy Response Factor ($E_R$)
  - the Second Law concern
    - Entropy Generation Ratio ($R_{EG}$)
Energy Response Factor

• Energy Response factor accounts quantity of energy fed into or extract from a given TES

• defined as normalized change in total energy stored in the TES

\[ E_R = \frac{\Delta E_{\text{real}}}{\Delta E_{\text{ideal}}} \]

• Definition of “Ideal” reference processes:
  – for charging/discharging processes:
    • Adiabatic piston-in/outflow, zero mixing
  – for storing process:
    • thermal conduction heat transfer within the storage
    • heat losses to the ambient
• total entropy change is calculated as:

\[ \Delta S = \int_{V} \rho \cdot \Delta s \cdot dV \approx \sum_{i=1}^{n} m_i \Delta s_i \]

• \( \Delta S_i \) can directly obtained from volume discretized CFD simulation

• assume the system is adiabatically isolated from the ambient

• enables the isolation of irreversible (\( \Delta S_{ir} \)) part of \( \Delta S \)
• definition for the real process

\[ \Delta S_{\text{real}} = \Delta S_{\text{ir,real}} \]

• consider the same system as ideal stratified

\[ \Delta S_{\text{stratified}} = \Delta S_{\text{ir,stratified}} \]

• consider the same system as fully-mixed

\[ \Delta S_{\text{mixed}} = \Delta S_{\text{ir,mixed}} \]
Entropy Generation Ratio

- maximum difference between
  \[ \Delta S_{\text{mixed}} - \Delta S_{\text{stratified}} \]
- used to normalized entropy generation
- the entropy generation ratio is:

\[
R_{\text{EG}} = \frac{\left( \Delta S_{\text{real}} - \Delta S_{\text{stratified}} \right)}{\left( \Delta S_{\text{mixed}} - \Delta S_{\text{stratified}} \right)}
\]
Definitions of TES Efficiencies

Two Storage Evaluation Number (SEN) based efficiencies

• for charging / discharging processes:

\[
\eta_{SEN1} = \left[ 1 - \frac{R_{EG}}{E_R} \right] \cdot 100\%
\]

\[
= \left[ 1 - \frac{\Delta S_{real} - \Delta S_{stratified}}{\Delta S_{mixed} - \Delta S_{stratified}} \cdot \frac{\Delta E_{ideal}}{\Delta E_{real}} \right] \cdot 100\%
\]
Definitions of TES Efficiencies

• for storing process:

\[ \eta_{SEN2} = \left[ 1 - R_{EG} \cdot E_R \right] \cdot 100\% \]

\[ = \left[ 1 - \frac{\Delta S_{real} - \Delta S_{stratified}}{\Delta S_{mixed} - \Delta S_{stratified}} \right] \frac{\Delta E_{real}}{\Delta E_{ideal}} \cdot 100\% \]

• \( \eta_{SEN1} \) and \( \eta_{SEN2} \) increase as the charging-discharging or storing process approach its respective ideal processes

⇒ They behave like efficiency definitions
Sample Applications to HWSHS Design

Large sizes (500 – 10000m³)

- Design optimization based on field or laboratory data impractical

- CFD-based design and characterization shows great potential for storage optimization

- Analyses of typical short time periods offers new insights
Application 1: Charging/Discharging Process

- SEN Efficiency vs. Aspect Ratio

![Graph showing the relationship between Average $\eta_{SEN}$ [%] and Aspect Ratio. The graph has data points at Aspect ratios of 0, 1, 2, and 3, with corresponding SEN efficiencies of approximately 72%, 74%, 76%, and 78% respectively. The aspect ratio is defined as $H/D$.]

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Application 1: Charging/Discharging Process

- SEN efficiency vs. Side Angles ($\theta^\circ$)

![Graph showing SEN efficiency vs. Side Angles (\theta^\circ)]
Application 2: Storing Process

• SEN efficiency vs. Thickness of the wall

![Graph showing SEN efficiency vs. Thickness of the wall]
General Procedure for Design Analysis

CFD based design and optimization is most suitable for seasonal hot water stores

General procedure:

• CFD analysis of typical yearly scenarios within HWSHS should be carried out

• variation of design parameter

• estimation of SEN efficiencies gives the direction of optimization

This information may be used to optimize the design and operation of HWSHS.
Thank you for your attention!

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