Thermal energy storage and thermal management using PCMs: heat transfer enhancement and advanced modelling

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Overview

• Introduction
  • Latent heat thermal energy storage (LHTES)
  • Solid-liquid phase change modeling
  • Close-contact melting (CCM)

• CCM in tube and shell finned storage units
  • Units with radial or longitudinal fins
  • A novel configuration with a helical fin

• Modeling of CCM
  • Models designated for specific configurations
  • Advanced general model that allows convection in the melt coupled with solid bulk motion
Thermal energy storage (TES)

- Energy storage systems correct the mismatch between supply and demand of energy

- Thermal energy can be stored by elevating or lowering the temperature of a substance, changing its phase, or both

- Thermal energy storage has numerous applications:
  - Storage of solar energy for heating or power generation
  - Utilization of industrial waste heat
  - Hot or cold electrically generated thermal energy for use in off-peak hours

Different types of TES

- Commonly, thermal energy storage systems are classified by storage mechanism (sensible, latent, or chemical)

- In sensible heat storage systems, the storage medium can be a single phase liquid, e.g. water, oil, molten salt, or a solid, e.g. concrete or ceramics

- For latent heat storage solutions, the storage medium is a phase change material (PCM), which undergoes phase transitions associated with energy absorption and release dictated by its latent heat
Latent heat thermal energy storage

- Storage systems that utilize PCM can be advantageous in comparison with sensible storage systems
- The usually high latent heat of fusion allows a higher energy density, which enables size and cost reduction of the system
- PCMs absorb heat at an almost constant temperature, which allows minimal temperature losses in the discharge process
- These features make latent heat thermal energy storage (LHTES) attractive for different promising applications, such as storage for solar-thermal power plants

Latent heat thermal energy storage

- Although there are many promising applications, heat transfer design and media selection for LHTES systems are more difficult
- It is also known that materials with high latent heat of fusion have a low thermal conductivity
- This impedes the heat transfer rates to the PCM during the charging and discharging processes
- Moreover, during melting/solidification a thick layer of liquid/solid is formed between the heat transfer surface and the PCM
- This layer creates a thermal resistance that further decreases the heat transfer rate
Heat transfer enhancement

- Highly conductive porous matrices

- PCM enhanced with conductive nanoparticles

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Heat transfer enhancement

- Fins and other extended surfaces

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Ho-Kon-Tiat, V., Palomo del Barrio, E., Recent patents on phase change materials and systems for latent heat thermal energy storage, Recent Patents on Mechanical Engineering 4, (2011) 16-28
Radially finned storage unit

- The thermal storage charging/discharging process is driven by a hot/cold heat transfer fluid (HTF) inside the tube that causes the PCM to melt/solidify.

Longitudinally finned storage unit

- Storage units with three- and four-longitudinal fins
Solid-liquid phase change modeling

- Stefan problem formulation
  - Two heat equations coupled via Stefan condition

**Liquid phase:**
\[
\rho c_p \frac{\partial T_i}{\partial t} = \nabla \cdot (k_i \nabla T_i)
\]

**Solid phase:**
\[
\rho c_p \frac{\partial T_s}{\partial t} = \nabla \cdot (k_s \nabla T_s)
\]

**Stefan condition:**
\[
k_s \nabla T_s \cdot \mathbf{n} - k_i \nabla T_i \cdot \mathbf{n} = \rho L \mathbf{v} \cdot \mathbf{n}
\]

- Enthalpy method formulation
  - One equation, the solid-liquid interface is not tracked explicitly

\[
\rho \frac{\partial h}{\partial t} = \nabla \cdot (k \nabla T)
\]

\[
T = \begin{cases} 
T_w + \frac{h}{c_t} & h < c_r (T_s - T_w) \\
T_s - \frac{c_r (T_s - T_w)}{c_r} & c_r (T_s - T_w) < h < c_r (T_s - T_w) + L \\
T_w + \frac{h - L}{c_r} & h > c_r (T_s - T_w) + L 
\end{cases}
\]

Shamsundar and Sparrow, 1975

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Enthalpy-porosity method

Full solution of the conservation equations:

- **Continuity:**
  \[
  \nabla \cdot \mathbf{u} = 0
  \]

- **Momentum:**
  \[
  \frac{\partial (\rho \mathbf{u})}{\partial t} + (\rho \mathbf{u} \cdot \nabla) \mathbf{u} = \mu \nabla^2 \mathbf{u} - \nabla p - C \frac{(1 - \gamma)^2}{\gamma^3 + \varepsilon} \mathbf{u} + \frac{\rho \beta (\bar{h} - \bar{h}_{\text{ref}})}{c_p} \mathbf{g}
  \]

- **Energy:**
  \[
  \frac{\partial (\rho \bar{h})}{\partial t} + \nabla \cdot (\rho \mathbf{u} \bar{h}) = \nabla \cdot (\alpha \nabla \bar{h}) - \frac{\partial (\rho \Delta H)}{\partial t} - \nabla \cdot (\rho \mathbf{u} \Delta H)
  \]

\[
\Delta H = \begin{cases} 
L & T > T_i \\
\gamma L & T_i < T < T_s \\
0 & T > T_s 
\end{cases}
\]

Voller and Prakash, 1987
State-of-the-art modeling
- Enthalpy-porosity combined with Volume of Fluid (VOF)
- Takes into account air-PCM interaction

Solidification in a spherical shell
- Combination of VOF with the enthalpy-porosity method also enables to predict the transient development of a central void
Melting in a Hybrid PCM-Air Heat Sink


Modeling: Radial storage unit

Modeling: Longitudinal storage unit


Key questions

- The previously shown examples indicate that the solid bulk is stationary
- Therefore, two questions are of interest:
  - What would happen to the rate of melting if the solid is allowed to move?
  - How to model this process in order to obtain a reliable prediction?
Close-contact melting (CCM)

- The solid bulk is melted on a hot surface
- A thin molten layer is formed between the solid and the surface
- The liquid is squeezed to the sides by the descending solid

Experimental setup

1- Thermostatic bath, 2- Control faucet, 3- Perspex tank
4- Storage device, 5- Flow meter, 6- Immersion thermostat

Comparison: Radial unit

- Melting time without CCM is 42 min
- Melting time with CCM is 18 min

The role of fins is much more important than just to commonly serve as extended surfaces for heat transfer enhancement!


Comparison: Longitudinal unit

- Melting time without CCM is 48 min
- Melting time with CCM is 19 min

New idea: maximizing advantages

- Enables an entirely continuous volume of the PCM, which allows thermal convection unlike small and closed compartments.
- Enables a complete connection of the envelope to the fins, and leads to sinking of the solid and its "close-contact" melting.
- Because of the continuous volume, the PCM easily expands or shrinks, so that voids are excluded.
- In addition, mechanical stresses on the system parts are prevented, and this because there is no local increase in the pressure.
- The proposed configuration makes the filling, emptying and cleaning of the system much easier.

Melting: CCM is successfully realized

Solidification: connected volume, no voids

Absence of voids means high reliability and repeatability


Modeling CCM

- The experimental results indicate that CCM in finned storage units are advantageous
- It is thus desirable to model this type of systems in order to predict their performance
- However, the enthalpy-porosity method, which is implemented in many commercial CFD software packages, cannot model properly CCM
- Hence, three approaches are developed:
  - Simplified analytical models that can reveal the dimensionless groups that govern the problem
  - Advanced numerical models that are designated for a specific configuration
  - Development of a general method like the enthalpy-porosity method
Radial unit: Modeling approaches


Experimental validation

Longitudinal fins - CCM modeling

\[
\frac{d\alpha}{d\left(FoSte^{1/4}\right)} = \frac{8\alpha Pr \rho^\alpha \left(R^\alpha + R^\alpha + 1\right)\left(1 - \cos\left(\phi - \alpha\right)\right)}{3\left(R^\alpha - 1\right) \left(R^\alpha + 1\right) \left(3R^\alpha + 1\right)}
\]


Helical fin: CCM modeling

Advanced Modeling: In-house Code

- While being successful the models presented above are suitable for particular cases
- We aim to develop a more general model
- The new model takes into account convection in the melt
- Various simplifications such as thin-layer approximation are not needed
- This model can also take into account the solid bulk sinking motion and its coupling with the flow in the melt

Model Formulation

- Full solution of the conservation equations
- Enthalpy method based formulation
- A 2-D staggered grid is utilized

Assumptions
- Volume-change is neglected
- Boussinesq approximation is applied
- Material properties are constant
- The flow is laminar and incompressible
- The material is pure
- The solid bulk can move only in the y-direction
- The solid bulk is continuous and contains no "holes"

The equations:

Continuity: \[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0
\]

Momentum: \[
\frac{\partial u}{\partial t} = -\frac{\partial (u^2)}{\partial x} - \frac{\partial (uv)}{\partial y} + \frac{\mu}{\rho_s} \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) - \frac{1}{\rho_s} \frac{\partial p}{\partial x} + f_x
\]

Energy: \[
\frac{\partial H}{\partial t} = -\rho_f c_p \left[ \frac{\partial (uT)}{\partial x} + \frac{\partial (vT)}{\partial y} \right] + k \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right)
\]

Force balance: \[
\rho V_e \frac{dU}{dt} = - (\rho_s - \rho_f) g V_e + \int \left[ -p \hat{n}_x + \mu \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) \hat{n}_x + 2 \mu \frac{\partial v}{\partial y} \hat{n}_x \right] \, dS
\]
Solution Procedure

1. Solve the energy equation for the enthalpy:

\[
\frac{\hat{H}_{i,j}^{n+1} - \hat{H}_{i,j}^{n}}{\Delta t} = -\rho_s c_p \left[ u^r_{i,j} \left( T_{i,j}^{n} + T_{i,j+1}^{n} \right) - u^l_{i,j} \left( T_{i,j-1}^{n} + T_{i,j}^{n} \right) + v^r_{i,j} \left( T_{i,j}^{n} + T_{i,j+1}^{n} \right) - v^l_{i,j} \left( T_{i,j-1}^{n} + T_{i,j}^{n} \right) \right] + \frac{\Delta x}{2} \left[ \frac{v^r_{i,j} \left( T_{i,j}^{n} + T_{i,j+1}^{n} \right) - v^l_{i,j} \left( T_{i,j-1}^{n} + T_{i,j}^{n} \right)}{\Delta x} \right] + \frac{\Delta y}{2} \left[ \frac{v^r_{i,j} \left( T_{i,j}^{n} + T_{i,j+1}^{n} \right) - v^l_{i,j} \left( T_{i,j-1}^{n} + T_{i,j}^{n} \right)}{\Delta y} \right] + k \left[ \frac{T_{i,j}^{n+1} - 2T_{i,j}^{n} + T_{i,j+1}^{n}}{\Delta x^2} + \frac{T_{i,j}^{n+1} - 2T_{i,j}^{n} + T_{i,j+1}^{n}}{\Delta y^2} \right]
\]

2. Temperatures are updated according to the enthalpy to take into account the solid-liquid phase change:

\[
T_{i,j}^{n+1} = \begin{cases} 
T_m + \frac{\hat{H}}{\rho_s c_p} & \hat{H} < \rho_s c_p (T_m - T_m) \\
T_m & \rho_s c_p (T_m - T_m) < \hat{H} < \rho_s c_p (T_m - T_m) + L \\
T_m + \frac{\hat{H} - \rho_s L}{\rho_s c_p} & \hat{H} > \rho_s c_p (T_m - T_m) + L
\end{cases}
\]

Solution Procedure

3. Determine the solid bulk velocity \( U_s \) according to the force balance.

4. Move the solid bulk according to \( U_s \)
Solution Procedure

5. Predict velocities with no forcing - \( u^* \) and \( v^* \)

6. Distribute Lagrangian markers on the interface

\[
\delta(x - x_0) = \phi \left( \frac{x - x_0}{\Delta x} \right) \times \phi \left( \frac{y - y_0}{\Delta y} \right)
\]

where:

\[
\phi(r) = \begin{cases} 
\frac{1}{6} \left( 5 - 3|\mathbf{r}| - \sqrt{6(1 - |\mathbf{r}|)^2 + 1} \right) & 0.5 \leq |\mathbf{r}|; \\
\frac{1}{3} \left( 1 + \sqrt{3r^2 + 1} \right) & |\mathbf{r}| < 0.5; \\
0 & \text{otherwise}
\end{cases}
\]

7. Interpolate \( u^* \) and \( v^* \) to Lagrangian markers \( U^* \) and \( V^* \):

\[
U^*(\bar{x}) = \sum u^*(\bar{x}) \delta(\bar{x} - \bar{X})
\]

\[
V^*(\bar{x}) = \sum v^*(\bar{x}) \delta(\bar{x} - \bar{X})
\]
Solution Procedure

7. Interpolate $u^*$ and $v^*$ to Lagrangian markers $U^*$ and $V^*$:

$$U^*(\bar{X}) = \sum u^*(\bar{x}) \delta(\bar{x} - \bar{X})$$
$$V^*(\bar{X}) = \sum v^*(\bar{x}) \delta(\bar{x} - \bar{X})$$

8. Calculate the forcing at the Lagrangian markers – $F_x$ and $F_y$ to provide the solid velocities $u_f=0$ and $v_f=U_s$:

$$F_x^{n+1/2}(\bar{X}) = \frac{0 - U^*(\bar{X})}{\Delta t}$$
$$F_y^{n+1/2}(\bar{X}) = \frac{U^*_n - V^*(\bar{X})}{\Delta t}$$

9. Spread the forcing back to the grid via the discrete delta function:

$$f_x^{n+1/2}(\bar{X}) = \sum f_x^{n+1/2}(\bar{x}) \delta(\bar{x} - \bar{X})$$
$$f_y^{n+1/2}(\bar{X}) = \sum f_y^{n+1/2}(\bar{x}) \delta(\bar{x} - \bar{X})$$

At the inner solid part:

$$f_x^{n+1/2} = \frac{0 - u^*}{\Delta t}$$
$$f_y^{n+1/2} = \frac{U^*_n - u^*}{\Delta t}$$
Solution Procedure

10. Solve two Poisson equations for $u^{**}$ and $v^{**}$

$$u^{**n+1} = \frac{\Delta t}{2} \rho \nabla^2 u^{**n+1} = u^{*n} + \frac{f_x^{**n+1}}{\Delta t} - \frac{\Delta t}{2} \rho \nabla^2 u^n$$

$$v^{**n+1} = \frac{\Delta t}{2} \rho \nabla^2 v^{**n+1} = v^{*n} + \frac{f_y^{**n+1}}{\Delta t} - \frac{\Delta t}{2} \rho \nabla^2 v^n$$

11. Solve Poisson equation for the pressure correction:

$$\frac{1}{\rho} \nabla^2 \tilde{p} = \frac{\nabla \cdot (u^{**} + v^{**})}{\Delta t}$$

12. Calculate the new velocities, $u^{n+1}$ and $v^{n+1}$

$$u^{n+1} = u^{**} - \frac{\Delta t}{\rho} \nabla \tilde{p}_x$$

$$v^{n+1} = v^{**} - \frac{\Delta t}{\rho} \nabla \tilde{p}_y$$

13. Calculate the new pressure, $p^{n+1/2}$

$$p^{n+1/2} = p^{n-1/2} + \frac{H}{2} \nabla \cdot (u^{**} + v^{**})$$

CCM in a rectangular cavity

- Isothermal wall temperature
- Different parameters are studied:
  - Three aspect ratios
  - The effect of the wall temperature
  - Effects of convection in the melt
Melting in a square cavity

Example of the flow field
Comparison with the literature

Hirata et al. 1991

\[ \Delta T = 12 \, ^\circ C, \, t = 360 \, s \]

\[ \Delta T = 12 \, ^\circ C, \, t = 540 \, s \]

Hirata et al. 1991
Melting at non-quasi-steady conditions

0.1 s 0.2 s

0.3 s 0.4 s

Melting at non-quasi-steady conditions

1 s 100 s

200 s 300 s
Closing remarks

- The effect of close-contact melting (CCM) in finned latent heat thermal storage units is revealed and studied for the first time.

- It is found experimentally that CCM enhances the melting rate by at least 2.5 times in comparison with regular melting.

- A novel configuration with a helical fin is suggested and studied.

- Simplified analytical analysis reveals the governing dimensionless groups and basic features of the problem.

- A new numerical model combining the enthalpy-method with CCM modeling is developed and validated.

- The new model yields physically meaningful results for solid sinking and natural convection.