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# Containment capsule stresses for encapsulated phase change materials

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## HIGHLIGHTS

► EPCM to store thermal energy is considered for concentrated solar power systems.
► Finite element analysis is used to determine stresses in a cylinder containing PCM.
► Isothermal heat transfer to PCM enables efficient energy storage maximizing exergy.
► Elastic and plastic deformation of the encapsulating cylinder are investigated.
► The effects of point forces, cracks and dents are examined.

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## ABSTRACT

The encapsulation of a phase change material to store thermal energy is considered here for concentrated solar power systems. The stress distribution in a spherical nickel shell of 250 μ thickness formed around a ball of zinc by the electroless deposition process and a stainless steel cylindrical shell containing zinc are considered. The effect of external forces and imperfections within the shell structure that could affect the deformation are also modeled. The aim of the simulations performed is to establish a suitable thickness for the encapsulating material. It is concluded that while the shell can deform and safely withstand the anticipated expansion of the zinc, the added effects from point loads caused by the weight of the surrounding encapsulated capsules and other possible imperfections in the capsule structure could cause failure. A three-dimensional finite element model is used to establish the stresses in cylinders of different aspect ratio caused by the expansion of zinc as it melts inside of the encapsulation. The amount of void space that must be left inside of the capsule, so that the expansion of the zinc during phase change and the increase in gas pressure inside of the vessel will not cause failure of the shell, is determined from simulations. Results indicate that the cylinder with welded ends could easily contain up to 86% of the initial volume full of zinc with only a very small amount of plastic deformation, less than 0.5% strain, corresponding to an internal pressure of 2.03 MPa.



## 1. Introduction

Renewable energy, especially solar energy, technology is a rapidly growing industry because of current political and environmental issues [1–3]. Parabolic troughs, point collectors, and linear Fresnel collectors are used to concentrate solar energy for power generation. The distribution of solar energy over the surface of the earth is approximately 1 kW/m$^2$; however, the energy can only be collected in most places around the world for approximately 2000 h a year because of the night/day cycle, different seasons, and inclement weather. Efficient storage technologies are required to store energy for 4–24 h cycles to meet current power demands.

Energy storage in the form of latent heat of phase change materials (PCMs) is an efficient way of storing energy [4–9] since the process minimizes irreversibilites. The review papers and other references cited here bring out the state-of the art with respect to thermal energy storage technologies. Of specific interest are high temperature encapsulated phase change materials for thermal energy storage. Little work has been presented in the literature that deals with stress analysis related to such methods as encapsulation as well as other features that need consideration. The current attempts fill some of these gaps.

Use of PCM enables isothermal heat transfer at least for part of the stored energy. This minimizes entropy production for the isothermal energy exchange and the overall storage of energy. The

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Thermal Energy Storage (TES) group at Lehigh University considering an energy storage system that stores thermal energy with melting of (the phase change of) zinc or selected salts to be used. The system will melt the PCM by heat transfer from the fluid heated by solar energy to a temperature of 723 K. The zinc or salt PCM is then cooled and the energy regained from the packed bed heat exchanger at a high level of thermal efficiency and low entropy production. The phase change material, (zinc or salts), must be contained so that a large surface area-to-volume ratio can be maintained through consecutive heating and cooling (energy charging & discharging) cycles. The designed encapsulation containers must be resilient enough to hold the zinc through multiple heating and cooling cycles while withstanding the stresses at the relatively high temperatures (723 K).

A spherical nickel shell formed around a ball of zinc by the electroless deposition process and a cylindrical stainless steel shell with capped ends are investigated as encapsulation methods. Electroless plating is a well-accepted commercially viable process. The thicknesses of nickel considered for the encapsulation of zinc are those that are achievable by the electroless process. The analysis explores the viability and strength of such spherical microcapsules. The larger cylindrical steel encapsulated PCM capsules are to be manufactured with traditional cutting and welding shop practices. The larger cylindrical capsules were the most practical and cost effective method for thermal energy storage.

The stresses in the containers are calculated so that the thermal expansion and volume change of the zinc as it undergoes the melting process do not cause cracking or failure in the container (encapsulation), during the heating/cooling cycles. Chakrabarty [10], Timoshenko [11], and Mendelson [12] have presented the theoretical models for the stresses in the sphere and Budynas [13] has presented the models for the stresses in the cylinder.

The current work investigated different container geometries for use specifically in a packed bed for thermal energy storage. The plastic deformation of the encapsulating nickel sphere/stainless cylinder and the effects of point forces, cracks, dents, and thinning in the spherical nickel shell are investigated.

## 2. Theoretical analysis

The theoretical solutions for determining the stresses in both the spherical nickel shell and the cylindrical stainless steel shell are presented below. The equations analyze a thick-walled spherical shell or cylinder with internal radius of, $r_i$, external radius of, $r_o$, and internal pressure of, $p_i$, on the inner surface of the shell. Polar coordinates ($r$, $\theta$, $\varphi$) and cylindrical coordinates ($r$, $\theta$, $z$) are used to analyze the sphere and cylinder, respectively. Spherical symmetry is assumed in the nickel shell and an infinite cylinder is assumed for the steel cylinder. Assuming elastic deformation, the radial and tangential stresses ($\sigma_r$, $\sigma_\theta$) in both the sphere and the cylinder are functions of the radius ($r$), and satisfy the equilibrium equation as described in [10–13].

$$\frac{\partial \sigma_r}{\partial r} + \frac{a}{r}(\sigma_r - \sigma_\theta) = 0 \quad \begin{cases} a = 1 \text{ for cylinder} \\ a = 2 \text{ for sphere} \end{cases} \tag{1}$$

With the radial displacement denoted as, $u$, the stress–strain relationships for the shell in elastic deformation are as in Eqs. (2) and (3).

$$\varepsilon_r = \frac{\partial u}{\partial r} = \frac{1}{E}(\sigma_r - b\upsilon\sigma_\theta) \quad \begin{cases} b = 1 \text{ for cylinder} \\ b = 2 \text{ for sphere} \end{cases} \tag{2}$$

$$\varepsilon_\theta = \frac{u}{r} = \frac{1}{E}(c\sigma_\theta - \upsilon\sigma_r) \quad \begin{cases} c = 1 \text{ for cylinder} \\ c = (1-\upsilon) \text{ for sphere} \end{cases} \tag{3}$$

where ($\varepsilon_r$, $\varepsilon_\theta$) are radial and tangential strains $\nu$ is Poisson's ratio. Integrating the equilibrium equation, the Lamé solution is obtained and is shown in Eq. (4).

$$\begin{aligned} \sigma_r &= C_1 + \frac{C_2}{r^n} \\ \sigma_\theta &= C_1 - \frac{C_2}{(n-1)r^n} \end{aligned} \quad \begin{cases} n = 2 \text{ for cylinder} \\ n = 3 \text{ for sphere} \end{cases} \tag{4}$$

The boundary conditions $\sigma_r = 0$ at $r = r_o$ and $\sigma_r = -p_i$ at $r = r_i$ are applied to the sphere and the cylinder, and the stresses in the elastically deformed shell due to the Lamé solution are found and shown in Eq. (5).

$$\begin{aligned} \sigma_r &= \frac{-p_i\left(r_o^n/r^n - 1\right)}{r_o^n/r_i^n - 1} \\ \sigma_\theta &= \frac{p_i\left[\dfrac{r_o^n}{(n-1)r^n} + 1\right]}{r_o^n/r_i^n - 1} \end{aligned} \quad \begin{cases} n = 2 \text{ for cylinder} \\ n = 3 \text{ for sphere} \end{cases} \tag{5}$$

## 3. Solution method

The elastic model of the spherical shell is verified using the published specific solutions for well-known conditions. The internal pressure of the sphere at the elastic limit is denoted as "$p_e$" in Eq. (6). For a nickel shell thickness of 250 μ and a diameter of 25 mm the pressure at the elastic limit will be 2.3 MPa. An internal pressure of 0.3 MPa is used for the elastic test to ensure only elastic deformation of the sphere. The variables $Y$, $E$, $\nu$, and $u$ denote the yield stress, Young's modulus, Poisson's ratio and radial displacement, respectively.

$$p_e = \frac{2Y}{3}\left(1 - \frac{r_i^3}{r_o^3}\right) \tag{6}$$

$$u = \frac{p}{E}\frac{(1-2\nu)r + (1+\nu)\left(\dfrac{r_o^3}{2r^2}\right)}{\dfrac{r_o^3}{r_i^3} - 1} \tag{7}$$

For elastic deformation the difference between the tangential and radial stresses in the shell is less than the yield stress; $Y > \sigma_\theta - \sigma_r$.

The elastic deformation of the cylinder is verified using the published solutions for different internal pressures [11]. The pressures inside the cylinder are calculated using the combined gas law, assuming that the cylindrical container does not expand at all. The zinc expands much more due to thermal expansion as well as phase change and with a larger magnitude than the steel cylinder. The height and internal radius of the cylinder are denoted by $h$ and $r_i$. The fraction of the initial volume that is full of zinc at room temperature is denoted by $\%V_{zinc}$. The densities of zinc at 20 °C and 450 °C are 7135 kg/m$^3$ and 6244 kg/m$^3$, respectively. The initial ($T_{initial}$) and final ($T_{final}$) temperatures are 293 and 723 K and the initial gas pressure ($P_{initial\ air}$) in the capsule is 1 atm. The final air pressure is then determined using the gas law for a volume domain shown in Eq. (8).

$$P_{\substack{\text{final}\\\text{air}}} = P_{\substack{\text{initial}\\\text{air}}} \times \frac{1 - \%V_{zinc}}{1 - \%V_{zinc}\left(\dfrac{\rho_{\substack{20C\\Zn}}}{\rho_{\substack{450C\\Zn}}}\right)} \times \frac{T_{final}}{T_{initial}} \tag{8}$$

The pressures resulting from the equations based on initial zinc content and the tangential stresses resulting from the internal pressures are shown in Fig. 1. The internal gas pressure and