# Geometry optimization of a latent heat thermal energy storage unit using RT27

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**Abstract.** Geometry optimization of a latent heat thermal energy storage (TES) unit using RT27 is investigated to figure out an optimal shape which obtains the best heat transfer property. A 2D model of the TES unit is built for numerical analysis and simulation. By applying constructal method for calculation, the optimal shape factor is around 0.15. And 11 configurations are selected for comsol simulation, aiming at validating the constructal optimization procedure and analyzing the heat transfer process. According to the data analysis of the liquid fraction and heat flux from simulation results, the optimal shape factor is also around 0.15. In addition, it's found that boundary effect makes a big difference on the heat transfer process and the existence of the optimal shape factor can be validated in theory.

## Introduction

Thermal energy storage (TES) is a technology that stores the surplus thermal energy by heating the storage medium and release stored energy by cooling the storage medium when other energy sources cannot meet users' need. There are three kinds types of TES systems, namely: 1) sensible heat storage that is based on storing thermal energy by heating or cooling a liquid or solid storage medium; 2) latent heat storage using phase change materials; and 3) thermo-chemical storage using chemical reactions to store and release thermal energy [1].Nowadays, PCM is one of the most common heat storage media because of its large energy storage capacity [2].

At present, TES systems have been widely applied in humans' daily life to enhance the stability and availability of the energy supply. More and more researchers now combine TES and renewable energy in a power plant, like solar energy, to solve the intermittency problem of renewable energy. In Jinjia Wei's paper [3], paraffin wax FNP-0090 was used as the PCM and the spherical capsule of TES unit showed the best heat release performance. Taeil Kim optimized a latent heat thermal energy storage system with graphite foam as PCM for a concentrated solar power plant [4].

In this paper, a 2D model of TES unit is simulated by software comsol to validate the constructal method and deeply analyze the heat transfer process as well as the possible parameters affecting the heat transfer. All the work will be the basis of the following experiment and research for TES systems using high temperature PCM.

## Modeling

**Model Description.** As shown in Fig.1 (a) below, a 2D model is developed based on a rectangle with the length of L and height of H. It's symmetrical with copper fin in the middle section and PCM (RT27) provided on both sides. Heat source comes from the bottom of the copper fin, which represents a typical point to the volume model. Surrounding the model, it's the insulating material. Besides the internal heat transfer, there is external heat convection between the model and the

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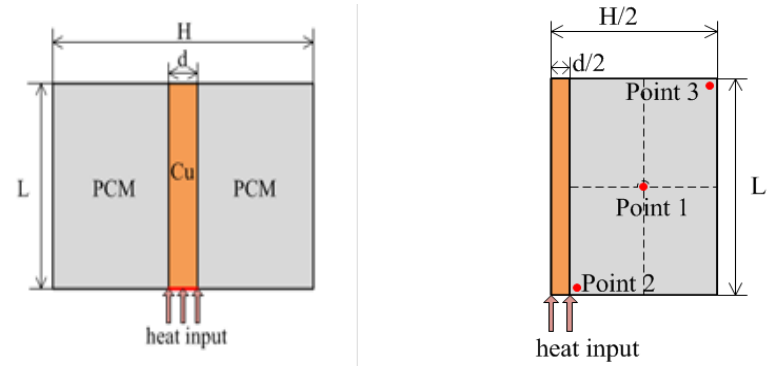
ambient. In fact, 3D model is viewed as a cuboid with the model depth of W. Shape factor ($f = H/L$), an important parameter about model geometry, is defined to conduct the optimization.




(a) (b)

Fig. 1 (a) Point to volume model, (b) 2D model in simulation

For simplification, only half model is simulated. And we choose three points in the PCM region to simulate and analyze their temperature variation process. As shown in Fig.1 (b), point 1 is located in the center of the PCM region, point 2 is in the bottom-left corner of the PCM region and point 3 is in the top-right corner.

RT27 is chosen as PCM to store thermal energy because of its low melting temperature and simple melting process and copper is used as the metallic fins material due to its high thermal conductivity. The properties of RT27 and copper are tabulated in Table 1.

Table 1 Property of RT27 and Cu

| Properties | Cu | RT27 | |
|---|---|---|---|
| | | Solid | Liquid |
| Density ρ (kg/m³) | 8940 | 870 | 760 |
| Thermal conductivity λ (W/m.K) | 392 | 0.24 | 0.15 |
| Heat capacity $C_p$ (J/kg.K) | 385 | 2400 | 1800 |
| Latent heat L (kJ/kg) | n.a. | 179 | |
| Melting temperature $T_m$ (K) | 1403 | 300 | |

**Numerical Model.** For geometry optimization of the TES model above, a kind of constructal method proposed by S.Tescari and P.Neveu can be applied to calculate the optimal shape factor [5]:

$$f = 2/\sqrt{\tilde{\lambda} \cdot \phi(1-\phi)} \tag{1}$$

where $\tilde{\lambda}$ is the conductivity ratio of conductive fin to reactive material and $\phi$ is the volume ratio of conductive fin to reactive material.

In this paper, $\phi$ is assigned a value 0.095 and $\tilde{\lambda}$ can be calculated using the data from Table.1. It is computed that the optimal shape factor is around 0.15.

As mentioned above, a PCM-based thermal energy storage unit relies on the latent heat of the PCM to perform. A heat source term Q (J/m$^3$) is defined to describe this ability:

$$Q = \rho L \cdot f_l(t) \tag{2}$$

where $\rho$ is density, $L$ is latent heat of the PCM, and $f_l(t)$ is the fraction of liquid into the PCM.

Given that Q and $f_l(t)$ vary with time, another thermal variable $\sigma_q$ (W/m$^3$) that describes the time integral of the heat source term Q is introduced below:

$$\sigma_q = \frac{\partial Q}{\partial t} \tag{3}$$

According to "phase field method" validated by Calvet et al. [6] and the formula derivation by D.Verdier et al. [7], the equation below can be used:

$$\frac{\partial f_l}{\partial t} = \beta(T - T_m) f_l \tag{4}$$

To simplify the computation of the model, the parameter β, which represents the synthesis of many parameters, is kept constant with the average value $0.0001\mathrm{K}^{-1}\mathrm{s}^{-1}$ [7].

**Some Parameter Values for Simulation.** Software comsol is used to develop a 2D model of the TES unit. In order to figure out the optimal shape factor in the simulation, 10 configurations are

selected besides the optimal shape from constructal method. And their geometry parameters are listed in Table 2.

Table 2 Size parameters of the 11 configuration for simulation

| f | L (mm) | H (mm) | d (mm) | S (mm²) |
|---|---|---|---|---|
| 0.037 | 268.33 | 10.0 | 1.0 | 2683.30 |
| 0.074 | 190.30 | 14.1 | 1.4 | 2683.23 |
| 0.15(fopt) | 134.16 | 20.0 | 2.0 | 2683.20 |
| 0.18 | 121.97 | 22.0 | 2.2 | 2683.34 |
| 0.22 | 109.52 | 24.5 | 2.5 | 2683.24 |
| 0.29 | 95.83 | 28.0 | 2.8 | 2683.24 |
| 0.43 | 78.92 | 34.0 | 3.4 | 2683.28 |
| 0.54 | 70.61 | 38.0 | 3.8 | 2683.18 |
| 0.60 | 67.08 | 40.0 | 4.0 | 2683.20 |
| 0.93 | 53.66 | 50.0 | 5.0 | 2683.00 |
| 1.34 | 44.72 | 60.0 | 6.0 | 2683.20 |

The input parameters for the simulation are as follows: the original temperature is 293.15K, the depth of the model is 8mm, the input heat is 0.2W and the convection coefficient is 1W/($m^2$.K).

## Results and analysis

**Analysis of the Heat Transfer Process.** There are two important performance parameters during PCM melting process, i.e. liquid fraction and heat flux. As shown in Fig. 2, we select the simulation data of four configurations to draw the graph of the liquid fraction varying with time. The increasing part of the curves that liquid fraction varies linearly with time are just the PCM melting process, which indicate that the whole phase change process is very stable. It's obvious that the PCM melting time is different with different model shapes. Geometry of TES unit will impact the energy storage speed.

As displayed in Fig.3 (a), the evolution trend of the three curves is consistent. They all have a certain segment that temperature almost keeps constant, which represents the PCM in these positions is melting. And this stable segment in point 1 is kept for the shortest time because point 1, located in the boundary of the PCM and the copper fin, is too close to the heat transfer interface. In addition, we can determine from the curve of point 3 that almost all the PCM is heated to its melting temperature at the time about 1400s because point 3 is the farthest point from the heat input point.

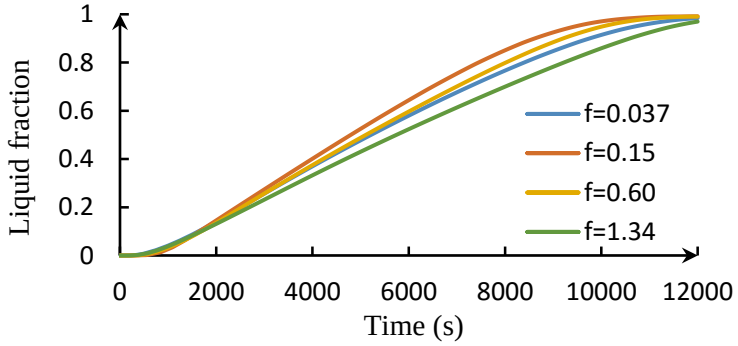
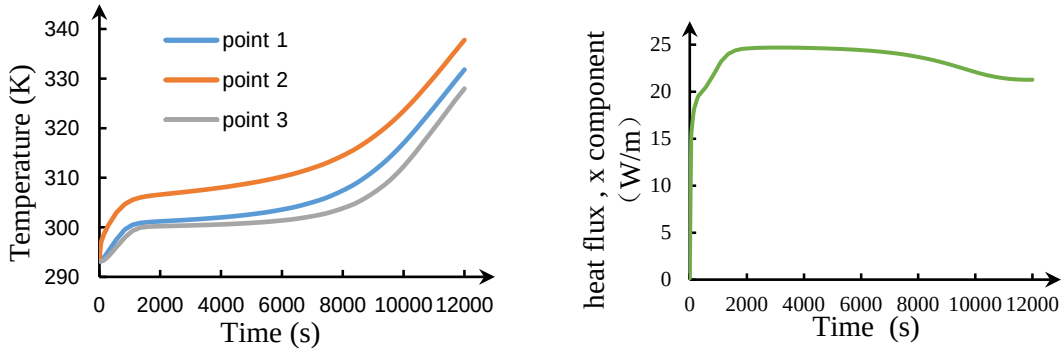



Fig. 2 Liquid fraction variation process of the PCM

In graph (b), the heat flux increases dramatically at the beginning due to the high thermal conductivity of the copper fin. Observing graph (a) and (b), we can find the heat flux through the boundary starts to keep constant when the temperature of all the PCM reaches 300K. Under ideal condition, the constant state should be lasted to the end, while graph (b) gives us a small segment with the heat flux decreasing and then returns to the constant state. As more and more PCM has been turned into liquid, the temperature of all the PCM will quickly increase, starting at the time about 8000s as shown in graph (a). The PCM near the point 3 has higher temperature than 300K

even if it's still liquid. So the heat transferred by the copper fin to the PCM will reduce in order to provide buffer time for the melt of the remaining solid PCM and balance the whole energy field.



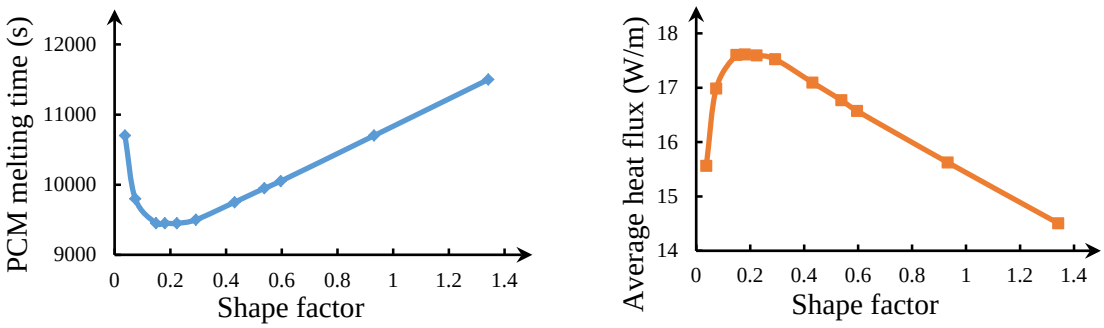

(a) (b)

Fig. 3 Temperature variation process of three points (a) and total heat flux through the boundary along x component (b) varying with time

For the whole heat transfer process, input heat is directly and longitudinally transferred to the copper fin and the copper fin transversely transfers the heat to PCM. As a result, there exists an optimal shape which can balance the heat transfer in the two directions to achieve a perfect charging and discharging capacity for TES unit.

**Optimal Shape Factor in Simulation.** Among all the shapes, there must be an optimal geometry which costs the least time totally melting the PCM and stores the most energy in the phase change process. Given that the point that the liquid fraction reaches 1 cannot be figured out exactly, the moment that the liquid fraction reaches 0.95 is chosen for analysis after simulation on the 11 configurations, as shown in Fig.4 (a). It's obvious that the optimal shape factor is around 0.15. In graph (b), the y axis, average heat flux, represents the average value of the surface integral of $\sigma_q$ in the PCM region during the period when the liquid fraction turns from 0 to 0.95. The result of the optimal shape factor is also around 0.15.

There is another similar point that graph (a) and graph (b) have. The PCM melting time and the average heat flux of the three point (f=0.15, f=0.18, f=0.22) only has a tiny difference. This characteristic can effectively allow the manufacture deviation of the TES unit.




(a) (b)

Fig. 4 PCM melting time (a) and heat flux (b) varying with the shape factor

## Conclusion

In this paper, we conduct the geometry optimization of a latent heat thermal energy storage unit using RT27 by means of numerical simulation. Applying existing constructal method for calculation, we find that the optimal shape factor is around 0.15. In simulation, 11 configurations are selected to figure out the design with the best energy storage property and the optimal shape factor is also 0.15. Analyzing the heat transfer process in simulation, we find that boundary effect is a significant influencing factor. Given that heat is transferred longitudinally in the copper fin and transversely in the PCM region, the model with the optimal shape factor can well balance the two factors and minimize their influence.

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