2022 Asia and Pacific Mathematical Contest in Modeling

Problem D

Structural Optimization of Heat Transfer Fins in the Energy Storage System

Efficient energy storage technology is the core technology to solve the volatility and intermittency of renewable energy and waste heat resources. Phase change heat storage is widely used because of its high energy storage density and heat storage and release at a nearly constant temperature. Solid-liquid phase change materials (PCMs) feature high latent heat and small volume change before and after phase change, which makes them comparatively easy to store and encapsulate. However, their generally low thermal conductivity factor leads to a prolonged heat storage and release process, which has become a key factor hindering the broad application of PCMs. To improve the rapid heat transfer capability of a heat storage system, we need to research the important topic to optimize the structural design and parameters of the system. At present, adding fin(s) has been widely used as a simple, economical, and effective means to enhance the solid-liquid phase change heat transfer process.

Fig. 1 Heat storage tank adopting phase change heat storage technology

A company needs to design the structure of heat transfer fins in the tank of the phase change heat storage system to further improve the heat transfer performance of heat storage products. The core component of the heat storage system is a shell-and-tube heat storage tank, as shown in Figure 1. The cross-section is shown in Figure 2. The circular ring needs to be filled with heat storage PCMs and fin structures. When the PCMs absorb heat, the high-temperature working fluid circulates in the inner tube, storing and utilizing its waste heat. When the PCMs release heat, the low-temperature working fluid circulates in the inner tube, absorbing and reusing the heat stored in the PCMs.

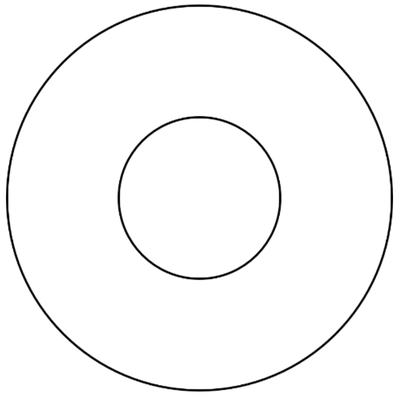

Fig. 2 Cross-section of phase change heat storage tank

The company plans to develop a small phase change heat storage tank, in which the inner radius of the tank is 0.02 m, the outer radius of the tank is 0.05 m, the thermal conductivity of the fins is 214 W/(m K), the density of PCMs is 780 kg/m3, the thermal conductivity of the phase change material is 0.15 W/(m K), and the phase change temperature is 333 K. The exterior of the tube is adiabatic, and the interior is filled with working fluid with a temperature of 373 K. Now your team is needed to answer the following questions to improve the heat transfer rate of the heat storage system.

Question 1: Assume that the cross-section of the heat storage tank with evenly distributed rectangular fins as shown in Fig. 3 is adopted. The length of rectangular fins is 0.018 m, the width is 0.006 m, and the interval angle between the fins is θ. PCMs in a solid state are heated by absorbing the heat energy of the working fluid in the tube. Please model the heat transfer process in the heat storage tank, optimize the interval angle θ, and state the time it takes for the average temperature of PCMs to rise from room temperature (293 K) to the phase change temperature in this case.

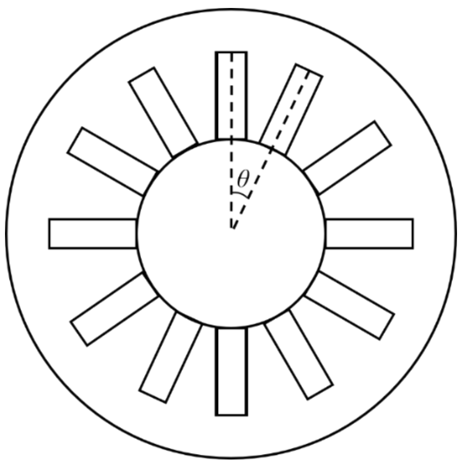

Fig. 3 Cross-section of phase change heat storage tank (rectangular fin structure)

Question 2: The shape and geometric size of the fins can have great influence on the heat transfer rate of the heat storage tank. Please take Fig. 4 as an example to optimize the size and distribution of triangular fins, study the influence of their size on the heating rate of PCMs, and compare and analyze their heat transfer effect with the rectangular fin structure in Question 1.

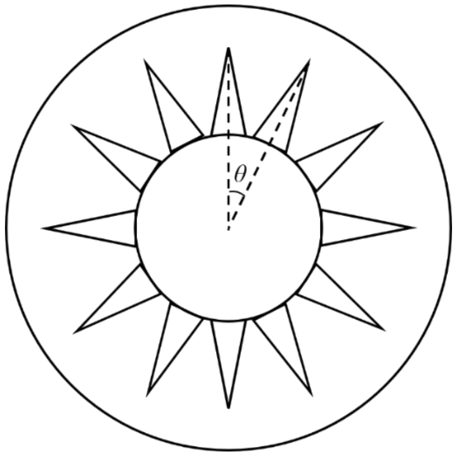

Fig. 4 Cross-section of phase change heat storage tank (triangular fin structure)

Question 3: Further optimize the design of the shape, parameters, and spatial distribution of fins to achieve the optimal heat transfer capacity of PCMs.

Question 4: Please write a letter to the company to suggest the fin design of the heat storage tank.