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Mathematical model of packed bed solar thermal energy storage simulation

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Abstract

Mathematical model has been developed to assess the effects of using phase change materials (PCM) in a fully mixed water accumulation tank. Packed bed system of spheres with a diameter of 40 mm have been considered as an option to increase energy storage density. A continuous phase model has been applied to analyse the influence of phase change during a charging and discharging processes. The methodology for calculating energy mass flow, density of water, heat transfer between layers, temperature for each time step and energy transferred to PCM is given. Single type of PCM with melting temperature of 55 °C and multiple type PCM system (65, 55, 45 and 35 °C) are compared. It is found that multiple type PCM system compared to only water and single type PCM systems, provide lower return temperatures and higher energy density.

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Keywords: spherical phase change; numerical analysis; multiple type PCM; heat accumulation

1. Introduction

Although solar water heating systems have been widely used around the world for many years, there are still many options to increase the efficiency of these systems. Some of the objectives are to improve thermal stratification, reduce heat losses and reduce temperature at the inlet of solar collectors. Thermal storage tanks are essential elements in solar systems, since they offset the availability of energy – sunshine during the daytime, and the use of energy – often in the evenings and mornings [1, 2].

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One way to increase the thermal density of a storage tank is to put a material with higher heat storage capacity in the water. There are submerged systems, where different shapes of containers are fixed at the bottom or top of the tank and packed bed systems, where the material is not fixed to the walls of the tank. Phase change materials (PCM) filled within containers are often used to make up the packed bed systems. Use of phase change materials have allowed to utilize latent heat storage. [3, 4]

Nomenclature

LH – latent heat, kJ/kg
Q – amount of thermal energy, kJ
T – temperature,°C
c_p – specific heat of the material used to store thermal energy($_p$ can be replaced by two brackets with number between them indicating specific PCM's melting temperature), kJ/(kg·°C)
ρ – density, kg/m^3
A – area, m^2
V – volume, m^3
Δt – time step, s
$\dot{V}$ – volumetric water flow, m^3/min
U – heat transfer coefficient, $W/m^2 \cdot K$
Subscripts
$_W$ – water
$_i$ – layer number
$_{cond}$ – conduction
$_{env}$ – environment
Superscripts
^{m} – moment

A lot of experimental work has been carried out to analyse solar systems, however the advancements in computational power has allowed mathematical models to thrive and become a more popular tool to analyse fluid flow and heat transfer problems within thermal storage systems. The first numerical analysis on systems with packed bed was conducted by Schumann [5] and many models created later have been based on Schumann's model [6]. Schumman's model considers that there is no heat conduction in the radial direction in the fluid and no heat exchange between particles.

There have been two main directions for describing packed bed systems. In the first case, each particle is taken into account and heat transfer is calculated between surfaces of particles and heat transfer fluid (HTF) [6–11]. In the second case it is considered, that the packed material, in this instance – PCM filled in capsules, behave as a continuous medium and not as a medium comprised of individual particles [12, 13].

Since both mentioned methods are limited, computational fluid dynamics have helped to take into account thermal gradients inside spheres, the complexity of the fluid flow and the heat transfer between the HTF and the porous media [14].

Study by Oró et al. [15] proposes three basic groups of models:

1. Continuous phase model: both the solid material and heat transfer fluid behaves as a continuous medium with conduction as the heat transfer mechanism;
2. Single phase model: for cases when the material has high thermal conductivity and high thermal capacity in comparison to the working fluid;
3. Thermal diffusion models or models with thermal gradient inside the particle: used if thermal gradient is considered within the solid particles and no inter-particle heat transfer and hence the temperature gradient at the particle surface will only be due to the heat transfer between the fluid and the bed.