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An enthalpy formulation for thermocline with encapsulated PCM thermal storage and benchmark solution using the method of characteristics

Eric Tumilowicz, Cho Lik Chan *, Peiwen Li, Ben Xu

Department of Aerospace and Mechanical Engineering, The University of Arizona, 1130 N. Mountain Ave., Tucson, AZ 85721, USA

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ABSTRACT

An enthalpy-based model of thermocline operation applicable to both single phase and encapsulated phase change filler materials was developed. Numerical simulation of the model was created using MATLAB. The method of characteristics was applied in space and time, mapping fluid temperature and filler enthalpy to a numerical grid, and in the case of a melting filler, allowed accurate tracking of PCM filler phase state interfaces to fractional positions of the grid. Careful consideration of various possible heat transfer conditions along with placement of PCM filler phase state interfaces in the numerical grid allowed for great versatility and accuracy in model application. Input of fluid and filler properties, tank size, time of operation, and initial and boundary conditions to the program returned a full representation to any desired amount of charge/discharge processes or cycles. The paper covers mathematical formulation, certain intricacies of numerical implementation, model verification, and the beginnings of application to prove proper operation and generality.

1. Introduction

With the constant expansion of modern civilization on a global scale, the gap between energy supply and energy demand continues to grow. Such a reality has driven many to investigate energy sources alternate to the typical fossil fuel offerings, of which solar is a great contender. Concentrated Solar Power (CSP) plants harvest the sun's radiation and convert the concentrated heat to electric energy. However, the resulting output is converted immediately, meaning the daylight supply does not correspond with evening peak demands [1]. To counteract this shortcoming, a thermal storage mechanism is applied, allowing a gathering of energy throughout hours of high solar density, to be discharged and applied as necessary at a later time. Of these storage mechanisms, we turn our attention to the thermocline.

Contrary to older two tank designs, the thermocline employs natural thermal stratification to allow thermal energy storage with a single tank – an obvious savings in material costs alone. For a charge process, initially cold fluid in the tank is extracted through the bottom, drawing in solar heated high temperature fluid into the top of the tank. This high temperature fluid heats the bed of filler material as it passes through, storing the thermal energy in the tank. When the stored energy is desired, the discharge process pulls the high temperature fluid from the top of the tank, to be replaced with cold fluid at the bottom, together extracting the energy back from the filler. The discharged high temperature fluid is used to drive an external power cycle [2]. A schematic of this process is included in Fig. 1 for full understanding.

In regards to thermocline filler material, the storage tank can operate on sensible heat, latent heat, or a combination of both. Based on properties alone, the use of a phase change material (PCM), combining both sensible and latent heat, allows a significantly higher energy storage density as compared to the use of sensible heat exclusively. Experimental studies of various tank filler materials confirm enhanced performance through use of a PCM, show resulting tank volume reduction by as much as a factor of 10, and suggest PCM fillers as fully viably alternatives for all thermal energy storage applications [3–6].

Efforts in thermal energy storage modeling go back as far as Schumann in 1929 [7], whose equations set the basis for representing fluid flow through a porous packed bed thermal storage tank. Following models [8,9] expand consideration, where most recently, Van Lew applied the method of characteristics to produce a direct, fast, and accurate numerical solution to model thermocline interactions [10]. A model by Felix Regin and Solanki [11] considered

* Corresponding author. Tel.: +1 520 621 2503; fax: +1 520 621 8191.
E-mail address: cholik@email.arizona.edu (C.L. Chan).

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Nomenclature

c_r^*	heat capacities ratio of PCM, solid to liquid
d_r	diameter of encapsules (m)
H	overall height of storage tank (m)
H_{CR}	dimensionless heat capacity ratio
h	heat transfer coefficient (W/m^2 K)
$\bar{h}$	enthalpy (J/kg)
k	thermal conductivity (W/m K)
Pr	Prandtl number
R	radius of storage tank (m)
Re	Reynolds number
r	radius of packed bed particle (m)
S	surface area (m^2)
S_r	surface area per length scale (m)
Stf	Stefan number
T	temperature (°C)
t	time (s)
U	axial velocity in storage tank (m/s)
V	volume (m^3)
Z	axial tank location (m)
Greek symbols	
ε	porosity of packed bed
η	dimensionless enthalpy
θ	dimensionless temperature
μ	dynamic viscosity (kg/m s)
ν	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
τ_r	dimensionless time scale
Subscripts	
f	refers to HTF
H	refers to the highest value of a variable
o	refers to the initial condition of a variable
L	refers to the lowest value of a variable
l	refers to the liquidus interface
r	refers to solid filler material
ref	refers to the reference value of a variable
r_ref	refers to a filler reference value
r_melt	refers to a filler melting point value
r_s	refers to the filler in a solid phase state
r_l	refers to the filler in a liquid phase state
s	refers to the solidus interface

a simple charge process of a tank with PCM filler for a parametric study of material properties. Following, a model by Wu et al. [12] applied an implicit finite difference method to solve the equations for the case with presence of PCM filler in the tank as a more general scenario, though results from the model featured numerous oddities and oscillations in temperature distribution profiles. To overcome the lower thermal conductivity of PCM material, Nithyanandam and Pitchumani [13,14] introduced heat transfer augmentation using thermosyphons or heat pipe. Different configurations were investigated by using CFD. Optimal orientation and design parameters were obtained. Archibold et al. [15] focused their attention on the fluid flow and heat transfer of the PCM within the spherical encapsulate. Recirculating vortexes were found in the upper region and therefore more intense melting occurs in this region. On the other hand, Vyshak and Jilani [16] used a modified enthalpy method to investigate the melting times for rectangular, cylindrical, and cylindrical shell storage configurations. The melting time was the least for cylindrical shell storage. They also investigated the effects of inlet temperature of the heat transfer fluid. Nithyanandam et al. [18] developed a transient numerical model for a latent thermocline storage system with encapsulated PCM. Repeated charging and discharging cycles were simulated to investigate the dynamic response. They presented a

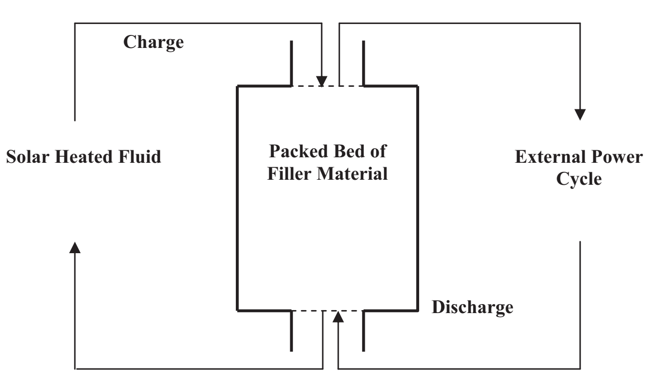

Fig. 1. General thermocline operation.

procedure for designing a thermocline tank packed with PCM. They found that using smaller encapsulated PCM greatly reduces the tank size. Flueckiger and Garimella [19] developed a new finite-volume approach to simulate the mass and energy transport inside a latent heat thermocline tank at low computational cost. System-level model, incorporating the transport model, was then developed to evaluate the viability of using latent heat storage. They found that thermocline tanks filled with a single PCM is not effective. They proposed a cascaded filler structure composed of multiple PCMs of different melting temperatures. In the present paper we proposed a robust, comprehensive, and highly accurate model for thermal energy storage with an encapsulated PCM filler.

The current work followed suite after the success of Van Lew, with a much-needed expansion of analysis to an encapsulated PCM filler [10]. An enthalpy-based version of the Schumann equations was used to allow tracking of interactions throughout the thermocline processes – a change especially necessary in the latent region where PCM filler temperature remained constant. The new set of equations was non-dimensionalized for general application. With the resulting equations being of hyperbolic type, the method of characteristics was applied for a numerical solution. The process gave fluid temperature and PCM filler enthalpy according to the discretized grid in time and space. With the equations following a similar form of those Van Lew obtained, we too expected the method to produce a direct solution that is both highly accurate and efficient.

The addition of enthalpy to consideration required an equation of state to close the gap in unknowns for solution. For proper application of this equation in the governing thermocline interactions, PCM filler phase states had to be tracked closely. More importantly, to maintain accuracy as these PCM filler phase states changes throughout the space, a careful tracking of PCM filler phase state interfaces had to be implemented as well. This allowed proper application of the equations to all possible orientations and conditions of the PCM filler phase state interfaces in the numerical grid of characteristics. The method of characteristics made this possible, though the extent of generality and versatility hinged on the completeness of physical cases considered in its application.