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CFD applications for latent heat thermal energy storage: a review

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ABSTRACT

Thermal energy storage is needed to improve the efficiency of solar thermal energy applications (STEA) and to eliminate the mismatch between energy supply and energy demand. Among the thermal energy storages, the latent heat thermal energy storage (LHTES) has gained much attention because of its high-energy densities per unit mass/volume at nearly constant temperatures. This review presents previous studies on the numerical modeling of phase change materials (PCMs) through a commercial computational fluid dynamic (CFD) software and self-developed programming to study the heat transfer phenomena in PCMs. The CFD (Fluent) software is successively used to simulate the application of PCMs in different engineering applications, including electronic cooling technology, building thermal storage, and heating, ventilation, air conditioning (HVAC). Using CFD software to design LHTES is believed to be an effective way to save money and time and to deliver optimization tools for maximum efficiency of STEAs.

Contents

1. Introduction

Researchers intensively studied the thermal energy storage of PCMs for the last three decades because of the latter's high thermal energy densities per unit volume/mass and their applicability to different engineering fields using wide temperature ranges. PCM thermal storage plays a key role in improving energy efficiency. It limits the discrepancy between the energy supply and the energy demand of solar thermal energy applications (STEAs), particularly when the STEA operation strategy depends solely on solar energy as a main source. PCM thermal storage indicates high performance and dependability with the advantages of high storage capacity and nearly constant thermal energy [1]. Most STEAs need constant or near-constant temperature for high-efficiency strategies. Using latent heat thermal energy storage (LHTES) as thermal energy storage can provide the required

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Nomenclature

C	Mushy zone constant (kg/m^3 s)
Cp	Specific heat of PCM, (J/kg)
g	gravity acceleration, (m/s^2)
h	sensible enthalpy(J/kg)
H	enthalpy (J/kg)
L	latent heat fusion (J/kg)
k	thermal conductivity (W/m K)
T	Temperature (°C or K)
u	velocity (m/s)

Greek letters

P	fluid density (kg/m^3)
γ	liquid fraction
β	volumetric expansion coefficient (1/K)
μ	Dynamic viscosity (kg/m s)
α	Phase volume fraction

Subscripts

ref	Reference
s	Solidus of the phase change materials
l	Liquidus of the phase change material

constant temperature that matches the melting temperature of the PCMs. PCMs are used in different engineering fields, such as in the following: the thermal storage of building structures [3–7]; building equipment, including domestic hot water; heating and cooling systems [8,9]; electronic products [10–12]; drying technology [13], waste heat recovery [14]; refrigeration and cold storage [15–18]; solar air collectors[19]; and solar cookers [20]. Using a CFD software to design a LHTES is expected to be an effective way to save money and time and to deliver optimization tools for maximum efficiency of STEAs.

2. Numerical solution of PCMs

The mathematical formulation of a phase transient known as a phase change or moving boundary is governed by a partial deferential equation that can be solved either analytically or numerically. The analytical solution of PCMs is problematic because of the nonlinear phase front interfaces, complex geometries, and nonstandard boundary condition; the few analytical studies available are on 1D cases with regular geometries and a standard boundary condition. Özisik [21] reported that the numerical method for solving PCMs can be categorized as fixed-grid, variable grid, front-fixing, adaptive grid generation, and enthalpy methods.

Predicting the behavior of phase change systems is difficult because of its inherent non-linear nature at moving interfaces, for which the displacement rate is controlled by latent heat lost or absorbed at the boundary [22]. The heat transfer phenomena in solid–liquid PCMs can be analyzed using two main methods: the temperature-based and enthalpy-based methods. In the first method, temperature is considered a sole dependent variable. The energy conservation equations for the solid and liquid are written separately; thus, the solid–liquid interface position can be tracked explicitly to achieve an accurate solution for the problems.

$$\frac{\partial T_s}{\partial n}k_s = \frac{\partial T_l}{\partial n}k_l + \rho L k v_n, \tag{1}$$

where T_s denotes the temperature in the solid phase, T_l denotes the temperature in the liquid phase, k_s is the thermal conductivity of the solid phase, k_l is the thermal conductivity of the liquid phase, n is the unit normal vector to the interface, and v_n is the normal component of the velocity of the interface. L is the latent heat of freezing, as shown in Fig. 1.

In the second method, the solid–liquid interface position need not be tracked. Researchers often use the enthalpy formulation because of the following advantages: (1) the governing equations are similar to the single-phase Eq.; (2) no explicit conditions need to be satisfied at the solid–liquid interface; (3) the enthalpy formulation involves the solution within a mushy zone, involving both solid and liquid materials, between the two standard phases; and (4) the phase change problem can be solved more easily [23].

$$\frac{\partial(\rho H)}{\partial t} + \nabla\cdot(\rho\overline{v}H) = \nabla\cdot(k\Delta T) + S \tag{2}$$

Where T denotes the temperature, k is the thermal conductivity, ρ is the density of the PCM, $\overline{v}$ is the fluid velocity, and H is the enthalpy, S is the source term.

Dutil et al. [22] presented an intensive mathematical and numerical review of the PCM application based on the first and second laws of thermodynamics. Using 252 references, they determined the mathematical and numerical methods applied to solve heat transfer problems involving PCMs for thermal energy storage, the mathematical fundamentals of PCMs, and the different application geometries and applications. Verma et al. [24] also introduced other PCM mathematical reviews.

Recently, researchers used the Fluent software by ANSYS to simulate melting and solidification in engineering problems. Other software that can be used to simulate the PCM process include COMSOL Multiphysics and Star-CMM+. However, Fluent is preferred by most researchers for melting and solidifying PCMs. Conversely, some researchers self-developed a program using computational language (C++, Fortran, Matlab) to study the heat transfer phenomena in PCMs. Table 1 summarizes some of the self-developed programs for different PCM geometries.

2.1. Fluent program

The Fluent software by ANSYS is a computational fluid dynamic (CFD) program used successfully to simulate different engineering problems. This software has a specific model that can simulate a range of different melting and solidification problems in engineering, including casting, melting, crystal growth, and

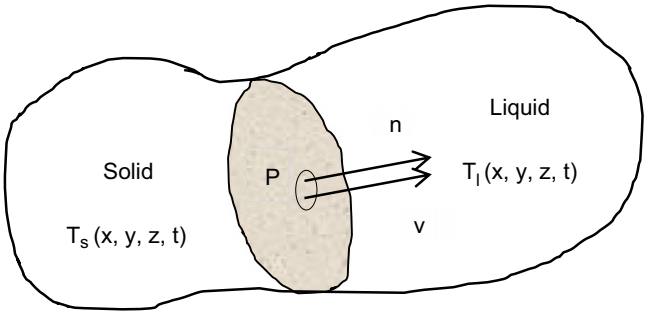

Fig. 1. Solid–liquid interface for a multidimensional situation [21].