Case Studies in Thermal Engineering 8 (2016) 128–140

Contents lists available at ScienceDirect

Case Studies in Thermal Engineering

journal homepage: www.elsevier.com/locate/csite

Latent energy storage: Melting process around heating cylinders

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ARTICLE INFO

Article history:
Received 20 May 2016
Received in revised form 22 June 2016
Accepted 22 June 2016
Available online 23 June 2016

Keywords:
Melting
PCM
Natural convection
Heat storage
Multiple cylinders

ABSTRACT

A physical model to investigate the melting process around a multiple of heating cylinders in the presence of the natural convection has been carried out. A numerical code is developed using an unstructured finite-volume method and an enthalpy porosity technique to solve for natural convection coupled to solid-liquid phase change. It is found that during the melting process around the cylinders, natural convection circulation around each cylinder interacts with the other cylinders to influence the melt shape. In addition to natural convection, the heat source arrangement is an important factor in determining the melt shape.

1. Introduction

Energy sources will play an important role in the world's future given that the global demand for energy is rapidly increasing. It is estimated that the consumption of electrical energy will double in the next 15–20 years [1]. Estimates of the world primary energy consumption are that 80% of the supply is provided by fossil fuels [2]. The primary energy use is estimated to rise between 32% and 84% by 2050 as compared to 2007 [3]. The greenhouse gas (GHG) emissions from electricity generation are approximately 40% of total emissions as most of that industry uses fossil fuels, particularly coal and oil, hence area leading contributor to global energy-related CO_2 emissions [4,5]. The impacts of climate change are now too evident to be disputed. As the Stern Review points out [6], it would be too costly to tackle the challenge of climate change if the world procrastinates in taking actions. Using renewable energy sources seems a promising option; however, there are still some serious concerns about some renewable energy sources and their implementation, e.g. (i) capital cost and (ii) their intermittent nature in power production [7–9].

Among the renewable energy sources, solar power generation undoubtedly offers the most promising and viable option for electricity generation for the present and future. By using adequate equipment sun irradiation energy can be converted into thermal and electrical energy. Depending on the temperature of the working fluid we can differ between the low-temperature ($T < 100$ °C), middle-temperature (100 °C $< T < 400$ °C) and high-temperature solar thermal energy conversion

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http://dx.doi.org/10.1016/j.csite.2016.06.010
2214-157X/

Nomenclature

c	specific heat capacity (J kg^{-1} K^{-1})
f	liquid fraction
$\vec{g}$	the acceleration of gravity vector (m s^{-2})
L_F	melting heat (J kg^{-1})
Nu	Nusselt number
p	pressure (Pa)
S	surface (m^2)
T	temperature (°C)
t	time (s)
$\vec{u}$	vitesse vector (m s^{-1})
V	control volume (m^3)
x	coordinate (m)

Greek symbols

$\bar{\bar{\tau}}$	the viscous stress tensor
λ	thermal conductivity (W m^{-1} K^{-1})
Γ	diffusion coefficient
μ	dynamic viscosity (kg m^{-1} s^{-1})
ρ	density (kg m^{-3})
β	the coefficient of volumetric thermal expansion (K^{-1})

Subscripts

i	initial
m	melting
nb	neighboring

(400 °C < T < 4000 °C). For low-temperature solar energy conversion one uses flat collectors with water and air, for middle temperature conversion one uses vacuum collectors and collectors with concentrators, and for high-temperature conversion one uses solar furnaces and concentrating solar power (CSP) plants [10,11].

In order for the renewable energy resources to become completely reliable as primary sources of energy, energy storage is a crucial factor [12,13]. Essentially, energy from these renewable resources must be stored when an excess is produced and then released.

The thermal energy storage (TES) can be defined as the temporary storage of thermal energy at high or low temperatures [14–16]. TES systems have the potential of increasing the effective use of thermal energy equipment and of facilitating large-scale switching. They are normally useful for correcting the mismatch between supply and demand energy [13,17–19].

Certainly, TES is of particular interest and significance in using this essential technique for solar thermal applications such as heating, hot water, cooling, air- conditioning, etc., because of its intermittent nature [20–23]. In these applications, a TES system must be able to retain the energy absorbed for at least a few days in order to supply the energy needed on cloudy days when the energy input is low. One of the thermal energy storage system concepts takes advantage of the latent-heat-of-fusion of phase change material (PCM) to store and recover thermal energy. A latent thermal storage system possesses three major components: (i) a heat storage system that undergoes a solid-to-liquid transformation within the desired operating temperature range, (ii) containment of the storage substance, and (iii) a heat exchanging surface for transferring heat from the source to the storage substance and from the latter to the heat load.

Solid-liquid phase change heat transfer relevant to latent heat-of-fusion energy storage systems has been a subject of many theoretical and experimental studies [24–27]. In this paper, we investigate numerically the heat transfer during the melting process of PCM around a multiple horizontal heat sources (see Fig. 1). This study is motivated by the need to gain improved understanding of heat transfer during the charging phase of TES system which takes advantage of latent heat-of-fusion of PCM. A relevant consideration in such systems is the effective utilization of the PCM by an optimum arrangement of tubes through which the working fluid is circulated. Good heat transfer characteristics between the transport fluid and the PCM for efficient thermal performance of a storage unit are also required [21,28]. Natural convection is also an important process in problems involving melting [29–32], and it is the purpose of this paper to point out some of its characteristics.

2. Mathematical formulation

The general assumptions considered in this work include transient formulation and two dimensional Newtonian incompressible fluid where the natural convection effects are considered. The thermophysical properties of the PCM are assumed to be constant but may be different for the liquid and solid phases. The Boussinesq approximation is valid, i.e., liquid density variations arise only in the buoyancy source term, but are otherwise neglected.

Since the present formulation deals with solutions on unstructured grids, it is essential to represent the conservation laws in their respective integral forms.

$$\int_S \vec{u}\,.\,\vec{n}\,dS = 0 \tag{1}$$

$$\frac{\partial}{\partial t}\int_V \rho\,\vec{u}\,dV + \int_S \rho\,\vec{u}\,\vec{u}\,.\,\vec{n}\,dS = -\int_V \vec{\nabla}p\,dV + \int_S \bar{\bar{\tau}}\,.\,\vec{n}\,dS + \int_V \vec{A}_U dV \tag{2}$$