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Transient multi-day simulations of thermal storage and heat extraction for a finned solar thermal storage device

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ABSTRACT

The effect of combining metal fins (Al) for heat spreading and recovery with phase change material (a mixture of $NaNO_3$ and KNO_3) on the performance of a thermal storage device is investigated. High-resolution transient simulations are performed covering two days of solar energy influx and heat extraction. The solver uses the enthalpy method to track melting, a strongly coupled implicit scheme to calculate conjugate heat transfer, and a dynamically refined mesh to ease grid creation and maximize computational efficiency. A potential application is thermal storage for solar cooking, although other applications can also be envisaged. The energy inputs of the simulations are based average solar radiation during a 48 h solar cycle in New Delhi, India in June with a 1.5 m^2 solar reflector. Four different fin designs for an insulated latent heat thermal storage device (TSD) to be used with a solar cooker are tested. The four designs are compared based on their ability to spread heat evenly and rapidly into the phase change material (PCM) and the ease with which heat can be withdrawn from the device for cooking. The tests demonstrate the potential for using long term, multiday numerical simulations in the evaluation of TSD designs.

1. Introduction

For several decades, there has been a growing interest in developing inexpensive, clean and efficient cook stoves for use in the developing world. This growing interest draws its impetus from multiple areas. Traditional cooking methods create significant economic, environmental, and health problems for communities around the world. The World Health Organization, for instance, reports that cooking smoke, trapped indoor in the cooking process, leads to approximately two million deaths a year, the vast majority of which take place in low or middle income countries (World Health Organization, 2009). Excessive harvesting of fire wood in areas with growing populations leads to deforestation and its accompanying environmental problems, and this deforestation in turn leads to the need, particularly among women and children, to spend a significant portion of the day in search of cooking fuel (Lewis and Pattanayak, 2012). Finally, the shortage of wood means that these individuals have less time to pursue longer term economic viability through education or cottage industry work (Vanschoenwinkel et al., 2014).

Solar cookers, in particular, offer an ideal solution to this problem: smokeless cooking done with abundant free energy. Engineers have done impressive technical work developing a range of efficient and workable solar cookers (Yettou et al., 2014; Panwar et al., 2012; Cuce and Cuce, 2013). But this has not led to the widespread adoption of solar cookers (Bansal et al., 2013). The chief cause of this failure is that the existing cookers have required that their users adapt their community cooking habits to the needs of the cooker. Cooking methods, available food, and traditional foods in developing areas are often quite particular to that community: many solar cooker designs do not take these particularities into account, and so people have been reluctant to adopt them. In response to this problem, there has been a more recent push to consider a "holistic framework" or "end-user" approach in designing a cooker and evaluating its success (Lewis and Pattanayak, May 2012; Vanschoenwinkel et al., 2014; Otte, 2014; Harmim et al., 2014). This has led some solar cooker researchers, for instance, to test the effectiveness of their cookers in the context of local food cultures (Tesfay et al., 2014; Dasin et al., 2015).

One result of this change in approach is a renewed interest in developing solar cookers that can provide a source of heat in the evening and morning. It is not surprising that most people, especially those in areas that might benefit most from solar cooking, traditionally prepare meals indoors and when the sun is not at

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Nomenclature

A	F_{liqud} nondimensional multiplier
Cp	heat capacity
F_{liquid}	liquid fraction of cell
g	gravitational force
L	length
t	time
T_{melt}	melting temperature
T	temperature
u	velocity in x direction
v	velocity in y direction
x,y	dimensional coordinates
σ_T	temperature standard deviation
α	thermal diffusivity
β	coefficient of expansion
ΔT	change in temperature
ν	kinematic viscosity
k	thermal conductivity
ε	half of phase change temperature range

Subscripts

ghost	condition at a ghost point
hot	condition at a heated wall
init	condition at time = 0
interface	condition at interface b/t fin and PCM
mtrl1	material 1
mtrl2	material 2

its peak. Many solar cookers, though, require that cooking take place during the day and in the outdoors. The development of an effective means to store solar heat, even if only through the evening hours, would be a step towards the creation of an attractive, end-user adapted cooker (Otte, 2014).

Perhaps the most promising approach to inexpensive small scale heat storage involves the use of phase change materials (PCM) as a medium for thermal storage systems (Agyenim et al., 2010; Dhaidan and Khodadadi, 2015; Muthusivagami et al., 2010). Latent heat storage systems have the advantage of lower temperature ranges and higher rates of energy storage per unit volume than sensible heat storage devices. Because the solidification process occurs over a significant time period at a known heat of solidification, they also offer the possibility of a long-lasting, steady-temperature source for cooking (Yettou et al., 2014; Mawire et al., 2010; Sharma et al., 2009, 2000).

However, the design of an efficient small-scale latent heat solar storage device presents significant challenges. A central difficulty in building an effective TSD lies in the low conductivity of most phase change materials. In order to melt the PCM as quickly as possible and to draw heat rapidly from the storage during discharge, it is necessary to find a way to move heat efficiently into and out of the device. Investigators have had demonstrated the effectiveness of numerous ways to do this, including the use of microencapsulation, interspersed high conductivity particles, and metal matrices, among others (Jegadheeswaran and Pohekar, 2009; Alkan et al., 2009; Sarı and Karaipekli, 2007; Mesalhy et al., 2005; Chen et al., 2008; Fan and Khodadadi, 2011).

The most common, simple, and low-cost strategy uses highly conductive finned structures to help conduct heat into and out of the PCM (Dutil et al., 2011; Gharebaghi and Sezai, 2007; Shatikian et al., 2008; Tiari et al., 2015; Long, 2010; Shokouhmand and Kamkari, 2012; Groulx and Ogoh, 2009). For solar cookers, this approach seems the most promising for two reasons. First, such cookers depend on concentrated solar energy on a single receiving surface. As a result it is necessary that the heat transfer enhancement technique be adaptable to the asymmetry of the temperature field, which is difficult to achieve using techniques such as high conductivity particles or a metal matrix. As a result, the finned core offers the best strategy to move large amounts of energy from the receiving surface into the interior of the TSD. Second, because the cost and the ease of construction and maintenance of the device must be kept in mind if a cooker is to be widely adopted, the simpler technology of a finned core is preferable to more recent technological developments such as microencapsulation.

Significant work has been done in recent years on using fins to enhance latent heat thermal storage (Gharebaghi and Sezai, 2007; Shatikian et al., 2008; Shokouhmand and Kamkari, 2012; Groulx and Ogoh, 2009; Shatikian et al., 2005; Akhilesh et al., 2005). Most of these works demonstrate the effectiveness of fins as a conduction enhancement strategy. Nearly all of them, however, acknowledge the heavy dependence of the effectiveness of the fins on the overall geometry of the model itself. Thermal behavior in phase change systems is highly dependent not only on viscosity and conductivity of the materials, but also on aspect ratio, container size, and specific geometry (Dutil et al., 2011). In other words, while the shape, length, volume, and placement of the fins is crucial to performance, there are no clear rules for fin design that apply across the myriad variations in PCM characteristics, container geometry, container material properties, and boundary conditions.

The complex interactions amongst these design variables make it difficult to compare the effectiveness of different cooker designs (Schwarzer and da Silva, 2008). In addition, dependable experimental results can be difficult to attain, because of the difficulties in observing and evaluating temperature fields, melting fronts, and convection patterns within a solid, opaque TSD. These complications makes numerical optimization appealing, and indeed much recent work on solar thermal storage devices has been done using simulations (Dhaidan and Khodadadi, 2015; Tiari et al., 2015; Fornarelli et al., 2016; Nithyanandam and Pitchumani, 2014; Liu et al., 2014).

But simulation of latent heat thermal storage in solar cookers comes with its own challenges. As detailed in previous work (Augspurger and Udaykumar, 2016), numerical difficulties are created by the complex geometries, the vastly different temperature gradients at the PCM/fin interface, and the combination of strong convection in melted regions with the low diffusivity of the latent heat medium. The scheme developed in that earlier work uses an adaptive locally refined octree Cartesian mesh to efficiently deal with complex geometries and the moving melt boundary. The enthalpy-porosity method is utilized to track the melting boundary. And an implicit single-field conjugate heat transfer method is combined with a sharp interface approach (Marella et al., 2005; Udaykumar et al., 2001) to calculate heat transfer between the solid core and the PCM.

However, there are further problems that this previous work did not address. These problems are related to the vastly different time and length scales inherent in a simulation of a TSD. On one hand, the real time scales for the solar cookers are very long: at the very least, it is necessary to simulate the hours between sunrise and sunset. In order to simulate thermal storage, at minimum a