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Solid–liquid phase change modelling of metallic sodium for application in solar thermal power plants

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Abstract

Liquid sodium presents a possibility for improved economics in concentrating solar thermal power plants. As the melting temperature of metallic sodium is above ambient temperatures (97.8 °C), melting of sodium in components will at times be necessary. A solid–liquid phase change model has been developed using Fluent for metallic sodium. The model was validated using a physical experiment in which metallic sodium was heated and cooled in a cylinder across the phase change temperature. The movement of the phase change front from the simulation was then compared to that of the physical experiment. The model was shown to be reliable and robust and had good correlation to the physical experiments. Examples of the beneficial use of this method in solar thermal systems are given, consisting of thermal storage systems, stem freeze seals and melting of the heat transfer fluid in receiver tubing.

Keywords: Concentrated solar thermal; Central receiver system; Metallic sodium; Phase change; Fluent; Solidification

1. Introduction

Molten salts are – at present – the predominant heat transfer fluid (HTF) used in heliostat-tower systems (Behar et al., 2013). Liquid sodium as the HTF is currently being explored as a possibility for reducing the costs of concentrated solar thermal systems due to its very high thermal conductivity, low melting point and high boiling point (Boerema et al., 2012; Pacio and Wetzel, 2013).

The present study was undertaken to develop a model for the prediction and visualisation of the solid–liquid interface movement in metallic sodium. The work was motivated by a need to understand this heat transfer process for the design and operation of components in concentrating solar thermal heliostat-tower systems.

As the melting temperature of metallic sodium is above ambient temperatures (97.8 °C), melting of sodium in components will at times be unavoidable. A Fluent model has been developed for simulation of the solid–liquid phase change. The model allows transient simulation of the movement of the phase change front along a component. The model was validated for both melting and freezing using a physical experiment in which metallic sodium was heated and cooled from one end of the cylinder to achieve a complete phase change. The movement of the phase change front from the simulation was then compared to that of the physical experiment.

The model allows the use of a well-established simulation programme that provides robust simulations with a relatively rapid rate of convergence. Geometry changes

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can also be incorporated easily, to allow design evolution. This model is intended to assist in the virtual testing and management of the melting of sodium within components, such as the solar receiver and system piping, and in the prototyping of components to allow for appropriate melting/freezing.

Due to the large change in enthalpies and thermophysical properties that occur with a phase change, achieving convergence in numerical simulations can be difficult. As such, many models for simulation of the interface behaviour of liquid metals have been developed which deal with specific circumstances and incorporate approximations to reduce computational time. Generally, these models are developed for casting processes and are designed for a specific use and to look at particular issues, such as surface defects and crystal formation, with an aim to improve processing conditions (Lee et al., 2013; Reikher and Pillai, 2013). Other studies tackle the issue of the phase change through the development of new solver methods (Guo et al., 2010; Sun et al., 2011; Huang et al., 2013). In the context of concentrated solar thermal systems, the exact nature of the phase change front, such as the “mushy” region and the crystal growth pattern, is generally not of interest. Instead, of value, is an ability to efficiently evaluate the phase of the HTF in a component under various conditions and at various points in time.

2. Applications

For a solar thermal plant utilising liquid metal as the HTF, various design and operational advantages exist in having a validated model for the simulation of components. Three applications are presented here to demonstrate the general practicality of the model.

One suitable application would be in calculating the rate of heat loss, temperatures and solid–liquid interface movement within a solar thermal active storage system such the cold tank of a two tank thermal storage system. During lulls in solar irradiance it is possible for the outer portions of the cold tank to freeze. In this situation, a validated model of phase change can assist plant operators in planning backup heating (such as gas heating) of the storage system during multiple days of low solar irradiance.

As with most complex hydraulic systems, delivery of the HTF from the thermal storage system to the solar receiver requires the use of many valves. Due to the chemically reactive properties of sodium, the low viscosity of liquid sodium and the high temperatures that solar thermal systems are operated at, sealing of the valve around the valve stem by using packing is often ineffective. As such, a stem freeze seal device is often incorporated, which is a section along the valve stem that the sodium is frozen in using finned surfaces (Foust, 1972). The length of the stem freeze seal required is a design application suitable for the presented model.

A third application is melting of frozen sodium out of a receiver. In a heliostat-tower system concentrated sunlight from the heliostat field is focused onto a receiver at the top of a tower. In general, the receiver will consist of a series of vertical side-by-side tubes (e.g. a billboard configuration as described in Boerema et al., 2013) connected between two headers. HTF is pumped through the receiver, where conduction and then forced convection delivers the energy from the concentrated sunlight to the HTF, thereby increasing its temperature. During long periods of low irradiation the HTF will be drained from the receiver. However, non-ideal system operation can lead to incidences of the HTF becoming frozen within the receiver. These situations include incorrect system shutdown, pump failure and excessive cooling during cloud transients. The HTF in the headers, which are insulated, can be reheated using electrical heat tracing. As the receiver tubes are uninsulated on the irradiated side, standard electrical heat tracing is not possible along the length of the tube, although it should be noted that they could employ resistive heaters on the back face before the insulation. Usually, though, a quantity of solar heat (with that quantity being defined using the fundamental knowledge gained from this study) would be used to melt the HTF in the receiver upon start up. Thus, melting of frozen HTF is usually possible through heating the base of the receiver (via the header) or through well-controlled solar energy from the heliostat field. A very specific flux density must be used such that the sodium is melted, whilst not allowing material temperatures to increase to those that could damage the tube material or lead to excessive stresses within the receiver. Since the density of liquid sodium is ~2.5% less than solid sodium (see Boerema et al., 2012), not much thermal stress is expected if there is room for expansion in the headers. If a molten salt were to be used in the receiver tubes, which thermal expansion of ~10% in going from liquid to solid, thermal stress could be a serious issue. By selecting the correct thermophysical properties, the model presented below could help to determine the extent and locations for which this is an issue for any HTF in a receiver tube. Overall, the model presented can be used to determine appropriate heat fluxes and melt times for this to be undertaken effectively.

3. Methodology

To validate the model, a physical experiment was undertaken in which metallic sodium was heated and cooled across the phase change temperature (97.8 °C) in a vertical cylinder, using heat transfer through the cylinder’s base. Temperature profiles of the sodium were recorded and compared with simulation results.

3.1. Physical experiment

A 500 mm long, 90 mm inner diameter cylinder, with 1.5 mm wall thickness was made of 304 stainless steel. The dimensions of this tube were chosen to be representative of a section of a commercial billboard receiver tubes. In order to fully characterise the heat losses this tube was