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ScienceDirect
Energy Procedia 69 (2015) 451 – 460
Energy Procedia

International Conference on Concentrating Solar Power and Chemical Energy Systems, SolarPACES 2014

Numerical model and validation for simulating the cold filling of the molten salt receiver tube

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Abstract

Anti-protecting against freezing and preheating the components are the most critical problems of molten salt receiver. Cold filling is a potential solution to these problems. This paper presents a numerical model for simulating the cold filling of a receiver tube. The model uses the volume of fraction method to track the interface between the molten salt and the air and the enthalpy method to describe the liquid-solid phase change of the molten salt. This model was used to simulate the cold filling tests of the Molten Salt Electric Experiment (MSEE) receiver. This model was then use to simulate the dynamic process of cold filling a vertical receiver tube. Three modes of cold filling, including successful filling, partial frozen filling and fully frozen filling, were demonstrated. The results show that high initial temperature of the receiver tubes is benefit for successful filling.

Peer review by the scientific conference committee of SolarPACES 2014 under responsibility of PSE AG

Keywords: Cold filling; Molten salt; Phase change; Solar central receiver;Introduction

1. Introduction

As economical, nontoxic, high heat capacity and low operative pressure [1], molten salts are widely used in concentrated solar power plants, such as Themis, Solar Two, Archimede and Gemasolar. Large scale concentrated

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Peer review by the scientific conference committee of SolarPACES 2014 under responsibility of PSE AG
doi:10.1016/j.egypro.2015.03.052

solar power plants using molten salts have low levelized electrical cost and great commercial prospect [2]. But, high freezing temperature is one of the biggest drawbacks of molten salts. The Hitec® heat transfer salt, 7% $NaNO_3$-53% $NaNO_2$-40% $NaNO_3$, and the Solar Salt, 60% $NaNO_3$-40% KNO_3, begins to freeze at 415 K and 511 K respectively [1]. Therefore, the flow loop of the salt should be warm by heat trace which increases the parasitic electrical consumption. In addition, certain absorb panels of the receiver have not heat trace or can't be preheated by concentrated sun light, so they needs several hours to be heated by conduction [3]. This limits the operation strategy and the availability of the plants and affects the efficiency.

Cold filling, which refers to running a fluid through tubes having temperatures are below the fluid's freezing point, is a candidate way to solve this problem. This paper described a numerical model to simulate the dynamic process of the cold filling of the molten salt into a receiver tube. The model was used to simulate the cold filling tests of the MSEE receiver [4]. Then the model was used to present three modes of cold filling: successful filling, partial frozen filling and fully frozen filling.

Nomenclature

A_0, A_1, A_2	Constant	Geek symbols	
C_0, C_1, C_2	Constant	ε	Constant
C_p	Thermal capacity (J kg^{-1} K^{-1})	γ	Volume fraction
f	Moody friction factor	μ	Viscosity (kg m^{-1} s^{-1})
f_{liq}	Volume fraction of liquid	ρ	Density (kg m^{-3})
g	Gravity (m^2 s^{-1})	ξ	Local pressure loss coefficient
h	heat transfer coefficient (W m^{-2} K^{-1})	ΔH	Latent heat (J)
k	Thermal conductivity (W m^{-1} K^{-1})	Δp	Pressure drop (Pa)
L	Length (m)	Δt	Time step (s)
L_H	Fusion heat (J kg^{-1})		
P	Pressure (Pa)	Subscripts	
Q	Flow rate (kg s^{-1})	a	Air
R	R coordinate	B	Bend
Re	Reynolds number	H	Horizontal tube
R_i	Inner radius (m)	i	Inlet
R_o	Outer radius (m)	liq	Liquid
t	Time (s)	m	Molten salt
T	Temperature (K)	out	Outlet
T_L	Liquidus temperature (K)	pu	pump
T_S	Solidus temperature (K)	R	Receiver tube
T_{wi}	Initial temperature of the tube wall (K)	s	Surroundings
V	Velocity (m s^{-1})	w	Wall
Z	Z coordinate	ref	Reference

2. Physical and mathematical model

2.1. Physical model

Fig. 1 shows a typical mode, referred as flood fill, of filling a multi-pass central receiver. All the drain and purge values are opened and the solar salt displaces air from lower headers to upper headers. During the process, the salt cools by the tube wall and solidification happens. As the solidification of the solar salt occurs in a range temperature between solidus temperature T_S and liquidus temperature T_L, a mushy zone exists between pure fluid and pure solid. T_S is the temperature at the interface between the solid and the mushy zones and T_L is the temperature at the interface between the liquid and the mushy zones. T_L and T_S are obtained from the phase diagram [5]. By symmetry the filling process can be simplified to a plane axisymmetric model, as shown in Fig. 2.