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Phase change of molten salt during the cold filling of a receiver tube

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Abstract

The most critical problems for the molten salt solar power plant are protecting against freezing and preheating of the flow pipes and equipments. A candidate way to solve these problems is cold filling. In this study, the dynamic process of molten salt cold filling into a receiver tube was simulated by combining the volume of fluid method and the enthalpy method. The detailed mechanism of melting-solidification and the evolution of the pressure drop along the tube were demonstrated. The influence of cold filling on the temperature across the tube wall was analysed as well. The results indicate that a lower pressure drop can be obtained by increasing the salt temperature and the initial tube temperature, and that an optimal velocity is required to get minimum pressure drop. The temperature difference between the external and internal surfaces of the tube wall increases with the filling velocity and the filling temperature whereas decreases with the initial tube temperature and the heat flux on the external surface. A large filling velocity and a high filling temperature that results in large temperature difference across the wall of the tube should be avoided. This study gives practical reference to the application of cold filling in molten salt receiver.

Keywords: Molten salt; Cold filling; Numerical simulation; Solar power tower plant

1. Introduction

As molten salts are economical, non-toxic, and functional at low pressure (Bradshaw and Carling, 1987), they are used as the heat transfer fluid and thermal storage material in solar thermal power plants. Over the past thirty years, several solar power tower stations which include Molten Salt Electric Experiment (Delameter and Bergan, 1986), Solar Two (Romero et al., 2002; Ortega et al., 2008), and Gemasolar (Burgaleta et al., 2011), successfully verified such kind of heat transfer fluid. However, the freezing point of molten salt is high, therefore heating the tubes to prevent the molten salt from freezing is essential for every molten salt power plant. During bad weather and night shutdown, the heat tracing still need to work to maintain the desirable temperature of the pipes of the molten salt. This increases the parasitic electrical power consumption of the plant. The installation of heat tracing reduces the reliability and efficiency of the plant.

A method to solve this problem is draining all the salt when the plant is shut down and then turning off the heat tracing of the major pipes such as the riser, down comer pipes, the receiver tubes, and headers, allowing these pipes cooling down. Then cold filling the pipes when the plant starts up. Cold filling refers to running a fluid through tubes having temperatures are below the fluid's freezing point. Bergan (1986) conducted three cold filling tests and pointed out that cold filling receiver tubes shortens the start-up time and prolongs the working time of receiver. It means the receiver can work at partly cloudy day and collect more solar energy. In addition, Pacheco

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Nomenclature

A_{mush}	mushy zone constant (kg m^{-3} s^{-1})
C_p	thermal capacity (J kg^{-1} K^{-1})
g	gravity acceleration (m s^{-2})
h	heat transfer coefficient (W m^{-2} K^{-1})
H	enthalpy (J)
k	thermal conductivity (W m^{-1} K^{-1})
L_H	latent heat (J kg^{-1})
L	length (m)
P_t	pressure drop along the tube (Pa)
Q	heat source term (W m^{-3})
D_i	internal diameter of tube (m)
D_o	external diameter of tube (m)
S	momentum sink (kg m^{-2} s^{-2})
T	temperature (K)
T_{so}	solidification temperature (K)
T_{cr}	crystallisation temperature (K)
T_{wd}	temperature difference between the internal and external tube surfaces (K)
T_{wi}	initial tube wall temperature (K)
$\vec{V}$	velocity vector (m s^{-1})
X, Y	coordinate (m)

Greek symbols

β	liquid fraction (–)
γ	volume fraction (–)
ρ	density (kg m^{-3})
σ	surface tension (N m^{-1})
μ	viscosity (kg m^{-1} s^{-1})

Subscripts

a	air
i	inlet
m	molten salt
max	maximum
s	surrounding
w	wall

(1995) and Pacheco et al. (1995) showed that cold filling benefits the absorber panels from being uniformly preheated before they are filled with molten salt. Through experiments Pacheco (1995) and Pacheco et al. (1995) proved the feasibility of cold filling of piping and receiver panels.

Cold filling is considered to be a moving boundary problem, also known as Stefan problem (Crank, 1984). Many researchers focus on analytical methods to understand the physical processes involved in moving boundary problems (Neumann, 1912; Goodman, 1958). Although analytical approaches provide exact solutions, these methods are limited to problems with simple initial and boundary conditions. Instead of analytical method, Cheung and Baker (1976) performed a series of tests to study the transient freezing of liquids in circular tubes and obtained an empirical formula to determine the penetration distance of cold filling. Through experimental observations, Gilpin (1981) studied the modes of ice formation in the tube during water cold filling. Although these studies are different, their results all agreed that solidification and melting phenomena appear in cold filling process and that blockage can occur if the tube is sufficiently long.

In recent years, with the development of computer capability, new CFD algorithms have been developed to deal with moving boundary problems, such as the volume of fluid (VOF) method (Hirt and Nichols, 1981) and the Eulerian method (Anderson and Jackson, 1967). The VOF method was developed for two or more immiscible fluids and usually applied to free-surface flows, dam break, jet breakup and filling. The Eulerian method usually applied to modelling multiple separated of multiphase flow. For solidification and melting problems, the enthalpy method (Voller et al., 1987), the equivalent heat capacity method (Budhia and Kreith, 1973), and the temperature-transforming method (Cao and Faghri, 1990) are designed for fixed-grid solution and are easy to be programmed. Besides, the advantage of enthalpy method is explicitly tracking the liquid–solid front. Conde et al. (2004) used the enthalpy method to simulate the solidification in a tube, and their results exhibited good agreement with experimental data. Combining the VOF method with the enthalpy method, Lu et al. (2010), demonstrated the solidification and melting behaviour during the cold filling process of a circular tube. The filling process described by Lu et al. (2010) is in a horizontal tube, the gravity has little effect on the pressure drop of the filling process.

However, in a solar power tower receiver, the flow path of the molten salt is vertical and the gravity significantly affects the pressure drop. Besides, the influences of varied cold filling conditions on the wall temperature remain to be studied. This paper employs a numerical model to simulate the process of a molten salt filling into a vertical cold tube. The model uses the VOF method to track the interface between the molten salt and air and the enthalpy method to simulate the liquid–solid phase change of the molten salt. This paper describes the evolution of the gas–liquid interface and the solidification and melting behaviour of cold filling. The effects of several factors on the pressure drop along the tube which indicate the degree of solidification, and on the temperature difference between the external and internal surfaces of the tube wall are analysed as well. All the results can be used as a reference to the application of cold filling in molten salt receiver.