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Numerical and experimental investigation of melting with internal heat generation within cylindrical enclosures

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HIGHLIGHTS

- A numerical investigation is presented using computational fluid dynamics (CFD), of melting with internal heat generation for a vertical cylindrical geometry.
- An experiment was performed to produce such data using resistive, or Joule, heating as the internal heat generation mechanism.
- The numerical results are compared against the experimental results and showed favorable correlation.
- Uncertainties in the numerical and experimental analysis are discussed.
- Based on the numerical and experimental analysis, recommendations are made for future work.

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ABSTRACT

There have been significant efforts by the heat transfer community to investigate the melting phenomenon of materials. These efforts have included the analytical development of equations to represent melting, numerical development of computer codes to assist in modeling the phenomena, and collection of experimental data. The understanding of the melting phenomenon has application in several areas of interest, for example, the melting of a Phase Change Material (PCM) used as a thermal storage medium as well as the melting of the fuel bundle in a nuclear power plant during an accident scenario. The objective of this research is two-fold. First a numerical investigation, using computational fluid dynamics (CFD), of melting with internal heat generation for a vertical cylindrical geometry is presented. Second, to the best of authors knowledge, there are very limited number of engineering experimental results available for the case of melting with Internal Heat Generation (IHG). An experiment was performed to produce such data using resistive, or Joule, heating as the IHG mechanism. The numerical results are compared against the experimental results and showed favorable correlation. Uncertainties in the numerical and experimental analysis are discussed. Based on the numerical and experimental analysis, recommendations are made for future work.

1. Introduction

A typical melting problem [1] consists of a phase change material (PCM) in solid phase with the boundary temperature greater than the melting point of the PCM. This results in heat transfer from the surroundings to the PCM at the wall. In this case, the heat source for the melting process was the temperature gradient at the wall due to warmer surroundings. In another case, let the temperature of surroundings be the same or less than the temperature of the PCM and include a PCM with a uniform volumetric heat source (per unit volume of PCM). This can result in melting of the PCM due to this internal heat source.

There are different mechanisms for IHG such as nuclear reactions, chemical (exothermic) reactions, induction heating, etc. IHG can also be observed in a current carrying conductor. Many materials offer resistance to the flow of current through them, and these materials have a characteristic value of resistivity. Since metals are good conductors of electricity, their resistivity is very

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Nomenclature

A	cross-sectional area (m^2)
c	specific heat at constant volume of fluid (J/kg °C)
D	radius (m)
g	acceleration due to gravity (m/s^2)
H	height (m)
I	electrical current (Ampere)
k	thermal conductivity (W/m °C)
L	length (m)
m_T	mass of alloy 255 associated with the thermocouple (kg)
P	power (J/sec)
$\dot{Q}$	heat generation rate per unit volume (W/m^3)
$\dot{q}$	heat generation at a thermocouple location (W)
R	electrical resistance (Ω)
Ra	Rayleigh number based on radius
r	electrical resistivity (Ω m)
T	temperature (°C)
t	time (s)
U_D	uncertainty associated with data acquisition system (°C)
U_o	overall uncertainty (°C)
U_T	uncertainty associated with thermocouple (°C)
V_T	volume of alloy 255 associated with the thermocouple (m^3)

Greek alphabets

α	thermal diffusivity (m^2/s)
Δh_f	latent heat of fusion (J/kg)
β	coefficient of thermal expansion (1/K)
ρ	fluid density (kg/m^3)
μ	dynamic viscosity of the fluid (Pa s)

low. Resistance offered by a conductor to the flow of current depends on the type of metal and its geometry (cross-sectional area and length). This value of resistance is given by the following relation [2]:

$$R = r \times \frac{L}{A} \tag{1}$$

where R is resistance of the conductor, r is resistivity of metal, L is length of conductor and A is the cross-sectional area of conductor. Power lost in overcoming this resistance appears as heat and is given by following relation [2]:

$$P = I^2 R \tag{2}$$

where P is power lost or heat produced per unit time, and I is current passing through conductor. This heating of a conductor due to its resistance is also known as resistive or Joule heating. If heat produced is more than the heat dissipated to the surroundings, then this results in a rise in temperature of the conductor. Over period of time, the temperature of the conductor can increase and reach its melting point. This causes melting of the conductor due to IHG by resistive heating.

There are various applications of IHG depending on their mechanisms. An accident within a nuclear power plant is an example of undesired melting due to IHG. Residual heat must be removed by a cooling system in order to prevent overheating of the fuel rods. An earthquake and tsunami hit Japan on March 12, 2011, which destroyed the external power supply of the Fukushima nuclear reactor [3]. This interrupted the cooling system which ultimately resulted in the melting of fuel rods. Such incidents make better modeling and understanding of melting with IHG processes even more important. Other applications of melting with IHG are exothermic brazing [4], resistance welding [5] and induction heating [6].

Some of the early work on melting with IHG was done by Cheung, Chawla and Pedersen [7]. They numerically studied the process of freezing and melting in a heat generating slab bounded by two semi-infinite cold walls. Crepeau and Clarksean [8] developed similarity solutions to analyze natural convection driven by internal heat generation. Crepeau and Siahpush [9] also used a quasi-static approach to derive equations for the movement of the phase front for materials with internal heat generation. It was applied to cylindrical, spherical, plane wall and semi-infinite geometries with constant surface temperature and constant surface heat flux boundary conditions. Tran and Dinh [10] used an effective convectivity model for the CFD simulation of core melt pool formation in a reactor pressure vessel lower head. Jiji and Gaye [11] analytically examined the one dimensional solidification and melting of a slab with uniform volumetric heat generation and results were applied to the solidification of nuclear material and melting of ice. Computational results for volumetric heat generation in a cylindrical plane wall and spherical geometries are compared to previous quasi-static solutions by Crepeau, Siahpush and Spotten [12]. Siahpush and Crepeau [13] also presented scaling analysis of convective melting with internal heat generation. Shrivastava, Williams, Siahpush and Crepeau [14] validated and used a commercial software package, FLOW 3D[1] for the numerical modeling of melting with IHG in vertical cylindrical geometry.

In all the work done so far, analytical and numerical methods were used to analyze the process of melting with IHG. Very few engineering experimental results are found in the literature for the case of melting with IHG. Therefore, the present work is focused on producing and comparing the experimental and numerical results for melting with IHG. An experiment for melting with internal heat generation was produced using the low melting alloy 255 [15,16] as the medium. The principle of resistive heating is used as the mechanism for IHG. FLOW 3D was used for simulating the problem and finding a numerical solution. Finally, the numerical results are compared against results obtained from the experiment.

2. Experimental analysis

2.1. Experimental setup

This experiment was based on the principle of resistive heating. In the experiment, Alloy 255, in a cylindrical geometry, was used as the conductor which undergoes melting due to resistive heating. It is a lead-bismuth eutectic alloy (44.5% Pb, 55.5% Bi by weight) with a density of 10,529 kg/m^3 at 124 °C [15,16]. Alloy 255 was placed inside a hollow cylinder of Teflon. Length, internal diameter and

[1] www.flow3d.com.