International Journal of Thermal Sciences 112 (2017) 211–221

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Experimental measurements in melting ingots in the melt of the same material

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ARTICLE INFO

Article history:
Received 19 February 2016
Received in revised form
18 September 2016
Accepted 19 October 2016

Keywords:
Melting
Ice
Metals
Alloys
Heat transfer
Dimensionless numbers
Natural convection
Nusselt
Rayleigh
Prandtl
Stefan

ABSTRACT

This study concerns the melting of ingots of different materials in melt of the same material. We investigated the pure materials ice, lead, tin, and zinc, the magnesium alloys AZ91 and AM50, and the aluminum alloy A226. We used melting pots made from steel (for Pb, Sn, Zn, AZ91, AM50) and clay graphite (for A226) with a volume of 16 L, inserted into a resistance furnace. Some experiments with AZ91 were also carried out in a 2500 kg industrial furnace. The ice ingots were melted in a 20 L beaker. The temperature profile adjacent to the melting ingot was recorded over time. From this profile, the mean temperature of the melt adjacent to the ingots was calculated. Together with the geometrical and thermophysical properties of the investigated materials, the dimensionless Nusselt, Rayleigh, Prandtl, and Stefan numbers were calculated and interpreted as an empirical function, $Nu = 0.114 \cdot (Ra \cdot Pr)^{0.291} \cdot Ste^{0.754}$. This function describes the melting behavior of all of the materials considered. This partly agrees with results from the literature, but considerable deviations were also determined. Once the mean temperature is known, the time needed to melt the different materials in different geometrical shapes can be estimated along with the maximum melting rate. This simple model helps understand technical processes where melting of materials is relevant, for example when calculating energy consumption in the foundry industry.

1. Introduction

Casting processes require a rapid supply of molten liquid metal or alloys to the molds. The melting procedure includes the addition of ingots to an existing melt. Heat transfer and solid-liquid phase changes occur. Heat has to be transferred from the melt to the ingot. The transport mechanisms are conduction and convection through the solid-liquid interface to its surface. Initially, the temperature of the solid ice, metal, or alloy is raised from the starting temperature to the melting point or solidus temperature. Subsequently, melting occurs and heat for fusion has to be added. Finally, the liquid resulting from the ingot and the surrounding melt has to be heated up to the initial temperature. The duration of the procedure depends on the materials' properties, flow conditions, and temperature. The following presents a simple model to estimate the time needed to melt ingots.

Melting and solidification of pure materials and alloys are the subject of numerous scientific studies. Under defined experimental conditions, the melting behavior and particularly the interface shape and motion during melting have been investigated. These experiments are usually performed in rectangular test cells of different aspect ratios height/length with the two end walls serving as the heat source and sink. In such an experimental setup, Gau and Viskanta [1], Webb and Viskanta [2], and Beckermann and Viskanta [3], among others, investigated the melting behavior of gallium. Before melting, the temperature of gallium was held about 1–2 °C below the melting point. They calculated the Rayleigh number (Ra) and Nusselt number (Nu) using the average heat transfer coefficient with the height of the cell as characteristic length. The parameter $\frac{Nu}{Ra^{1/4}}$ decreased with the increase in dimensionless time Fo·Ste before levelling off at later times, indicating convection-dominated quasi-steady melting was reached. The characteristic length used for the Fourier number was the length of the cavity. Using an average melt layer thickness as the characteristic length, a simple relation between the dimensionless numbers

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http://dx.doi.org/10.1016/j.ijthermalsci.2016.10.010
1290-0729/

Nomenclature

A	surface of ingots
Gr	Grashof number
c_p	specific heat capacity
Nu	Nusselt number
H_F	latent heat of fusion
Pr	Prandtl number
g	gravitational acceleration
Ra	Rayleigh number
l_c	characteristic length
Ste	Stefan number
Q	total heat
Fo	Fourier number
q	heat per area and time
T	temperature
T_A	starting temperature of the melt
T_E	end temperature of the melt
T_P	starting temperature of the ingots
T_M	mean temperature of the melt
T_F	melting temperature
t	time

Greek symbols

α	heat transfer coefficient
β	coefficient of volumetric thermal expansion
δ	thermal boundary layer
η	dynamic viscosity
λ	thermal conductivity
ν	kinematic viscosity
ρ	density

Subscripts

l	liquid
s	solid

$\mathrm{Nu} = 0.0631 \cdot \left(\frac{\mathrm{Ra}}{\mathrm{Ste}}\right)^{0.274}$ was obtained, which is valid in the conduction, transition, and convection regimes [1,4]. However, in this case the characteristic length changes with time. The effect of solid sub-cooling was also investigated by Beckermann and Viskanta [3], with temperature differences up to 20 °C and 15 °C for the solid and for the liquid from the fusion temperature of gallium, respectively. The equation $\mathrm{Nu} = 0.5\ (\mathrm{Ra}\cdot\mathrm{Pr})^{1/4}$ correlated the results of the experiments in the convection dominated region. The study by Jany and Bejan [5] identifies the basic scales and regimes of melting with natural convection in an enclosure heated from the side. The four regimes are pure conduction, mixed conduction and convection, convection, and shrinking solid with increasing time. The study assumes laminar and two-dimensional liquid flow, negligible density difference between the solid and liquid phases, a Prandtl number greater than one (Pr = 50 for octadecane), and that all properties are constant, with the exception of the linear density-temperature relation. The height of the enclosure was chosen as the characteristic length. For the convection regime, the Nusselt number scaling law for Pr > 1 was $\mathrm{Nu} \sim \mathrm{Ra}^{1/4}$ and for Pr < 1 was $\mathrm{Nu} \sim (\mathrm{Ra}\cdot\mathrm{Pr})^{1/4}$. For the shrinking solid region, the heat transfer and melting rates depend on the size of the remaining solid. The timescale of the solid vanishing phase is assumed to be relatively insensitive to the shape of the solid. The case where the solid is at a considerably lower temperature than the melting temperature was also mentioned, when the additional effect of conduction in the solid must be considered. The equation $\mathrm{Nu} = \frac{0.35\ \mathrm{Ra}^{1/4}}{[1+(0.143/\mathrm{Pr})^{9/16}]^{4/9}}$, provided by Lim and Bejan [6], covers the entire Prandtl range. In particular, Gobin and Bénard [7] discuss the case of Pr < 1, which is valid for melting metals by natural convection. A general expression of the time-dependent Nusselt number has been given, which approaches the constant Nusselt number, $\mathrm{Nu}_\infty = 0.29\cdot\mathrm{Ra}^{0.27}\cdot\mathrm{Pr}^{0.18}$, at long timescales for convection-dominated quasi-steady melting. Virag, Živić and Galović [8] describe the melting of ice of 0 °C at wall temperatures between 2 and 12 °C and surrounded by water and provide values for the dimensionless numbers Nu, Ra, Pr, and Ste. Bertrand et al. [9] and Gobin and Le Quéré [10] compare different physical models and numerical procedures in the low and high Prandtl number range. An overview of numerical methods for solving phase change problems is given by Voller [11]. Advances in solving conduction and convection melting problems, among others, are described in scientific papers by Hannoun, Alexiades and Mai [12], Huber et al. [13], and Kosec and Šarler [14]. The complete melting furnace heated by a plasma torch was numerically simulated by Carmona and Cortés [15] with a commercial CFD code, in order to calculate melting times, heat losses and temperature distributions. Numerically predicted melting times, using different calculation models, were in the range of 625–584 s. The experimental determined time was 671 s. However, the experimental setup and objective of this investigation is somewhat different from those in the studies mentioned above. The casting shop needs to know how much time is needed to melt an ingot of given mass and shape in a melt of its own material. The temperature of the fed ingots is much lower than the melting point or liquidus temperature of alloys. The solid-liquid boundary of the ingot moves in all directions, associated with a decrease in surface area with time. With some strong simplifications, we tried to find a valid relationship between the dimensionless numbers Nu, Ra, Pr and Ste which could describe the relevant parameters to optimize the melting conditions for the pure metals Pb, Sn, and Zn, the magnesium alloys AZ91 and AM50, and the aluminum alloy A226. By measuring the temperature of the melt in the direct vicinity of the melting ingot together with the thermophysical and geometrical data, such an equation has been developed. As an example of a material with Pr > 1, ice ingots were also melted in water and tested. The addition of the solid materials to the melt approximately corresponds to the experimental conditions of the "shrinking solid" case described by Jany and Bejan [5], where predominantly natural convection occurs. However, in the present experiments the additional effect of conduction while heating the solid ingot to the melting temperature has to be considered, and is included in the overall Nusselt number. Additionally, in the majority of cases the temperature of the liquid phase is much higher than the melting temperature. The proposed method is an empirical approximation out of the lack of more detailed measurements regarding the timely and spatially changes of temperature and heat flux in the ingots and the melt. Thus, only an overall heat transfer coefficient could be calculated.

2. Experimental

Melting behavior was investigated for the pure metals lead