Materials Science and Engineering A 393 (2005) 338–343

MATERIALS SCIENCE & ENGINEERING A

www.elsevier.com/locate/msea

Electromagnetic damping of convective contamination in self-diffusivity experiments with periodic heating conditions

Y.Y. Khine, R.M. Banish*

Department of Chemical and Materials Engineering, Center for Materials Research, University of Alabama in Huntsville, Huntsville, AL 35899, USA

Received 3 February 2004; received in revised form 26 October 2004; accepted 2 November 2004

Abstract

Accurate mass diffusivity values are important in mass transfer processes. Diffusion experiments conducted on earth are typically convectively contaminated due to either thermal or solutal gradients. Liquid metals and semiconductors have high electrical conductivities, and applied magnetic fields may suppress buoyant convection in these liquids. In this paper, an axisymmetric self-diffusivity model is considered in the presence of a steady, strong, uniform axial magnetic field with liquid indium. An isopycnic (radioisotope) tracer is used so that only thermal differences drive the convection. Five different combinations of a steady, uniform heat flux and a steady, periodic heat flux are imposed along the vertical wall while uniform heat loss is allowed through the top and bottom walls of the cylinder. The addition of periodic heat flux with the reduced uniform heat flux has a positive impact on the output diffusivity results for the same applied magnetic field of 5.24 T.

Keywords: Convection; Mass transfer; Magnetic fields; Metals; Semiconducting materials; Self-diffusivity experiments

1. Introduction

Diffusion is an important component of solidification mass transfer processes. Accurate and reliable modeling of these liquid–solid processes requires corresponding accuracy of both impurity and self-diffusivities of the molten liquid as well as the solid. Presently, there are several different theoretical predictions of self-diffusivity in melts and its temperature dependence $D(T)$ [1]. Given a perfectly isothermal enclosure, self-diffusivity measurements should be insensitive to convective contamination. Therefore, it should be possible to determine accurate values of self-diffusivity and the corresponding $D(T)$. Practically, during self-diffusion measurements in the presence of gravity (terrestrial experiments), even a small non-uniformity in temperature in the melt may drive a buoyant convection that can result in erroneous values of measured diffusivity. This convection may be produced even with residual acceleration magnitudes characteristic of microgravity conditions. Verhoeven [2] emphasized that any horizontal component of a density gradient in the liquid results in a spontaneous convection with no threshold.

Alexander et al. [3] performed 3D time-dependent transport modeling and showed that horizontal temperature non-uniformities across the sample as low as 1 and 0.1 K can drive convective transport rates in 1 and 3 mm diameter capillaries that exceed the diffusive transport rates under terrestrial conditions (g_0). Experiments conducted by Persson et al. [4] showed that the concentration versus distance (squared) plots for vertical and horizontal capillaries both yielded linear fits even though the diffusivity values differed by a factor of 1.2. This is due to the fact that both purely diffusive behavior and convectively contaminated mass transport have the same solution form. Therefore, a linear fit is no guarantee that a resulting diffusion profile is free of convective contamination. The convective contamination of typical terrestrial data prevents a reliable choice of the temperature dependence of self-diffusivity, much less impurity diffusivities.

Efforts to obtain reliable measurements have concentrated on methods to dampen the convective contamination. Since

* Corresponding author. Tel.: +1 256 824 6969; fax: +1 256 824 6944.
E-mail address: banishm@uah.edu (R.M. Banish).

0921-5093/$ – see front matter
doi:10.1016/j.msea.2004.11.004

the electrical conductivity, σ, of liquid metals and semiconductors is very large, some researchers have applied magnetic fields to suppress the buoyant convection in the liquid during self-diffusivity experiments. Alboussiere et al. [5] determined that with Lorentz electromagnetic damping of convection in liquid metals and semiconductors, the convective contribution to the mass transport is scaled as Hartmann number Ha^{-4} which is a characteristic ratio of the electromagnetic body forces to viscous forces in the liquid.

In actual self-diffusivity experiments, the measured diffusivity results in the presence of buoyant convection that lie within 5% from the known real value, D_0, would be considered acceptable. In our previous paper [6], we presented a first self-diffusivity model with an applied, uniform, axial magnetic field. The model is assumed to be axisymmetric, and the results were presented for liquid indium with moderate magnetic field strengths (0.218 and 0.873 T) with different heat transfer conditions. This paper is a continuation of the previous work, and the purpose of this paper is to determine the allowable temperature non-uniformities in the liquid that will guarantee that the measured diffusivity values are within 5% of the actual value when the model is exposed to a strong, uniform, axial magnetic field (∼5 T). Five possible combinations of a steady, uniform and a steady, periodic heat fluxes are applied along the side wall as the driving force of buoyant convection in the liquid, and uniform heat losses are assumed through the top and bottom walls of the cylinder during the measurements. Note that the purpose of the periodic heat flux is to produce localized hot and cold regions along the vertical wall of the cylinder and its overall heat flux is zero. In our previous studies [6,7], the numerical results suggest that the application of an additional steady, non-uniform heat flux with the reduced steady, uniform heat flux have beneficial effects on the output diffusivity, D_{out}, results. Thus, the variation of heat transfer conditions is studied in this model with a strong magnetic field with intensity $B_0 = 5.24$ T. The simulated diffusivity results for liquid indium are presented in this paper.

2. Problem formulation

In this model, the liquid is assumed to be a Boussinesq fluid with a uniform density ρ. The fluid is contained in a closed vertical circular cylinder of length $Z = 30$ mm with an inside radius $R = 1.5$ mm, schematically shown in Fig. 1a. Gravity acts downward along the cylinder axis while a uniform axial magnetic field is applied in the opposite direction. For the dimensionless model, the origin lies at the centerline ($r = 0$), and $z = Z/2R$, the vertical wall lies at $r = 1$ and the top and bottom limits are at $z = 10$ and -10, respectively. The radioactive tracer is at the bottom of the cylinder at the beginning of the measurements.

In addition to the applied magnetic field of the magnet, an induced magnetic field may be produced due to the associated electric currents. The dimensionless equation governing the magnetic field flux density B for our model is

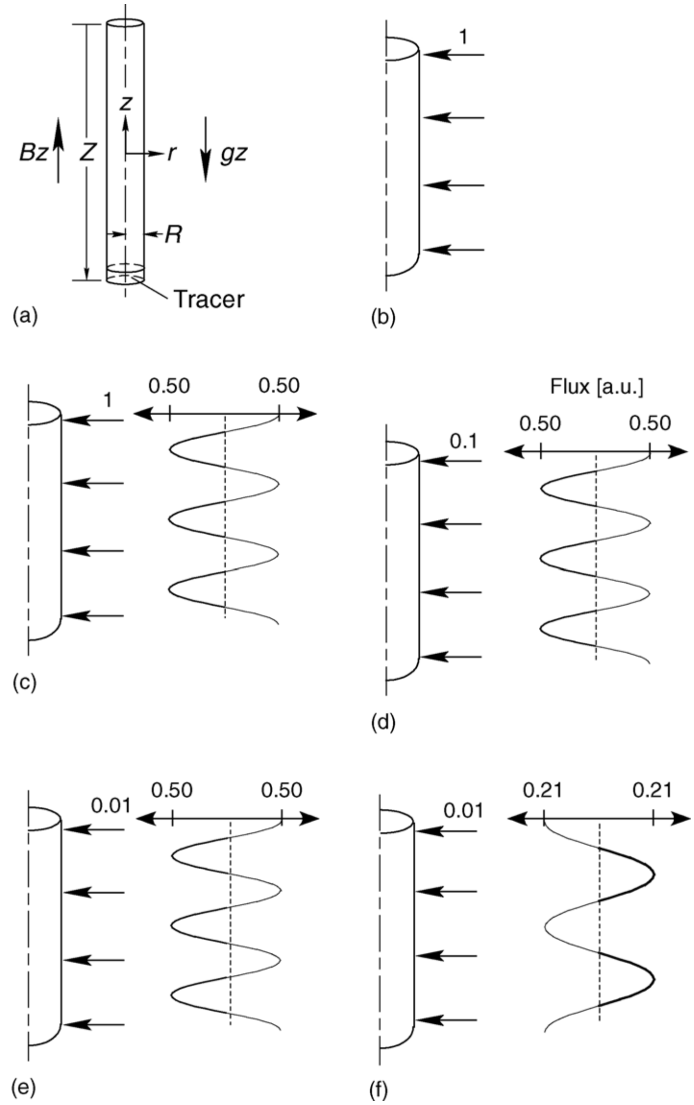

Fig. 1. (a) The schematic of the self-diffusivity model. (b–f) The set up with the dimensionless incoming heat fluxes for Cases I–V.

$$\nabla \times \boldsymbol{B} = R_m \boldsymbol{j}, \tag{1}$$

where $R_m = \mu_p \sigma U R$ with the magnetic permeability of liquid μ_p and a characteristic velocity U, is the magnetic Reynolds number which represents a characteristic ratio of the induced to applied magnetic field strengths [8], and j is the electric current density, normalized by $\sigma U B_0$. For liquid indium, R_m is in the order of 10^{-9} for this model. Since R_m is very small for self-diffusion experiments, the effect of the induced magnetic field is neglected in this model. The characteristic velocity U with a strong magnetic field is defined as in [6]:

$$U = \frac{2\rho g_0 \beta \, \Delta T_r}{\sigma B_0^2}. \tag{2a}$$

With a sufficiently strong applied magnetic field, $Pe = \rho c_h U R / k \ll 1$ where c_h is the specific heat and k