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Enhancement of oxygen transfer in liquid lead and lead–bismuth eutectic by natural convection

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Abstract

The present study carries out numerical analysis of the coupled natural convection and oxygen transfer of low-Prandtl-number (∼0.02) liquid lead and lead–bismuth eutectic (LBE) for testing and calibrating low concentration level oxygen sensors. The analysis is performed on the two-dimensional coordinates in a rectangular container, where the fluid movement is laminar for the purpose of sensor test and calibration. The oxygen supply is from the cover gas at the top of the container. Natural convection and oxygen transfer are examined under three temperature boundary conditions: (a) heated from the lower part and cooled from the upper part of the sidewalls of the container; (b) heated from the sidewalls and cooled from the top of the container; (c) one sidewall heated and the opposing wall cooled. It is found that there are four, two and one convective circulation cells under conditions (a), (b), and (c), respectively. All these flows induced by the natural convection greatly enhance the oxygen transfer in the liquid metal. The most efficient one is under condition (b), in which it takes about 1000 s for the oxygen concentration in the whole field to reach ∼90% of the input oxygen concentration from the top, instead of $\sim 10^6$ s by the pure diffusion.

Keywords: Oxygen transfer; Nature convection; Liquid metal

1. Introduction

Liquid lead or lead–bismuth eutectic (LBE) has been a primary candidate for high-power spallation neutron target and nuclear coolant due to its appropriate thermal–physical and chemical properties, such as low melting point, high thermal conductivity, and low vapor pressure [1]. However, lead alloys are very corrosive to common steels used in the nuclear installation [2]. This corrosion becomes a critical barrier in their applications. To reduce the corrosion, a protective oxide film needs to be built up at the interface of liquid metals and their steel carriers [3]. Unfortunately, it has been found that the pre-oxidation of steels does not prevent corrosion through the oxygen exchange in non-isothermal lead and bismuth systems based on the thermodynamic consideration [4]. Instead, a well-controlled extremely low oxygen concentration level (as low as 10^{-7} wt.% in

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Nomenclature

c, C	oxygen concentration (kg/m^3) and dimensionless oxygen concentration
$c_{\max}$	maximal oxygen concentration (kg/m^3), $C_{\max} = 1$
D	oxygen diffusion coefficient (m^2/s)
g	gravity acceleration (m/s^2)
$\mathbf{g}$	gravity acceleration vector (m/s^2)
k	oxygen mass transfer coefficient (m/s)
L	characteristic length (m)
m_c	mean oxygen concentration in the container
p	pressure (Pa)
P_{O_2}	partial pressure of O_2
Pe	Peclet number, U_cL/α
Pr	Prandtl number, $\mu/(\rho\alpha)$
R	Universal gas constant (8.3144 J/mol/K)
Ra	Rayleigh number, $g\beta\Delta\theta L^3\rho/(\mu\alpha)$
Re	Reynolds number, $U_cL\rho/\mu$
Sc	Schmidt number, $\mu/(\rho D)$
Sh	local Sherwood number, $Sh = kL/D$
$\overline{Sh}$	average Sherwood number
t, T	time (s) and dimensionless time
t_d	diffusion time scale, L^2/D
u, U	velocity (m/s) and dimensionless velocity component in the x-axis
U_c	Characteristic velocity (m/s), $U_c = \sqrt{\beta g L(\theta_{high} - \theta_{low})}$
v, V	velocity (m/s) and dimensionless velocity component in the y-axis
$\mathbf{v}$, $\mathbf{V}$	velocity vector (m/s) and dimensionless velocity vector
x	horizontal coordinate (m)
X	dimensionless horizontal coordinate, $X = x/L$
y	vertical coordinate (m)
Y	dimensionless vertical coordinate, $Y = y/L$

Greek symbols

α	thermal diffusivity (m^2/s)
β	thermal expansion coefficient (K^{-1})
μ	dynamic viscosity (kg/m/s)
ρ	density (kg/m^3)
θ, Θ	temperature (°C) and dimensionless temperature, $\Theta = \frac{\theta-\theta_{low}}{\theta_{high}-\theta_{low}}$
θ_0	reference temperature (°C)
θ_g	gas temperature (°C)
θ_{high}	higher temperature set on boundary (°C)
θ_{low}	lower temperature set on boundary (°C)
ω, Ω	vorticity (s^{-1}) and dimensionless vorticity, $\Omega = (L/U_c)\omega$
ψ, Ψ	stream function (m^2/s) and dimensionless stream function

liquid Pb and 10^{-10} wt.% in liquid LBE) is crucial in avoiding the corrosion of lead-alloy carriers as well as in avoiding the formation of lead oxide contaminations [5]. In order to uniformly and quickly mix oxygen of such a low concentration with liquid lead or LBE under high temperatures (350 °C–above 700 °C) for nuclear coolant applications, we propose a new method of using natural convection to enhance the oxygen transfer in liquid metals instead of mechanical mixing methods [6]. To guide our design for new mixing apparatus, we first numerically simulate oxygen-mixing processes in a 2-D rectangular container under different temperature conditions to study the natural convection mixing characteristics and estimate the time for concentration equilibrium.

Numerous researchers have been investigating the natural convection heat and mass transfer in an enclosure for a variety of applications, such as crystal growth [7], cooling of electronic component [8], and glass melting [9]. Heat transfer in liquid metal driven by natural convection in a cavity has been of considerable interest in crystal growth, purification of material, and many other fields [7,10]. Chu et al. [11] appeared to be the first to study the natural convection heat transfer from a discrete heat source in a 2-D enclosure filled with air. Later, Chadwick et al. [12] carried out both numerical and experimental studies of heat transfer on the influence of discrete heat sources on natural convection in a rectangular enclosure filled with air. Selver et al. [7] investigated natural convection heat transfer of a liquid metal in vertical circular cylinders heated locally from the side. However, to our best knowledge, there is no study of mass transfer in liquid metal by natural convection. Viskanta et al. [13] studied the 3-D liquid metal flow in a cavity. This study demonstrated that the average Nusselt number calculated from a 2-D analysis can be used as a first approximation to predict heat transfer in a 3-D cavity for low-Prandtl-number fluids such as liquid metals. Therefore, we perform our numerical simulation based on a 2-D rectangular container.

Measuring oxygen concentration in high temperature (>350 °C) liquid lead or LBE can be achieved reliably with the solid electrolyte sensors [14]. A zirconia-based solid electrolyte sensor for the oxygen-concentration measurement in LBE has been developed by Darling and Li [6]. However, the characteristics of this sensor have not been well examined. One application of our current study is to design a well-controlled system for