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地上での液体金属拡散実験で対流を抑制する Ra 数の条件

Rayleigh numbers for suppressing convection in ground-based diffusion measurements of liquid metals

山中亜里紗[1], 登林兼丸[1], 小林由央[1], 椎木政人[1,2], 鈴木進補[1]
Arisa YAMANAKA[1], Kanemaru NOBORIBAYASHI[1], Yoshihiro KOBAYASHI[1],
Masato SHIINOKI[1,2] , and Shinsuke SUZUKI[1]
1 早稲田大学, Waseda Univercity
2 ドイツ航空宇宙センター, Deutsches Zentrum für Luft- und Raumfahrt

1. Introduction

Diffusion coefficients in liquid alloys are industrially important for understanding the diffusion phenomena. Natural convection should be suppressed to measure diffusion coefficients accurately. A stable density layering which is the density increases monotonically in the direction of gravity is used to suppress natural convection in ground-based measurements 1,2). However, in some cases of impurity diffusion experiments with a small concentration difference, the conditions for stable density layering are not clear because of the density difference caused by a slight temperature distribution in the sample. The objective of this study is to identify the conditions for suppressing natural convection in impurity diffusion measurement expressed as Rayleigh number (*Ra*). Computational Fluid Dynamics (CFD) was performed to evaluate the *Ra* correctly under complex density and temperature conditions.

2. Experimental and analytical methods

Diffusion experiments were conducted using the shear cell technique at 973 K. The diffusion couples were Al-AlSn (labeled Cap. A, B, C, and D) and prepared with four different initial concentrations of Sn (c_0 = 0.05, 0.46, 1.55, 2.88 at.%, respectively). The main procedure of the experiment was the same as that in reference 3).

The fluid analysis was performed using the COMSOL Multiphysics® version 5.6 with the same dimensions as a capillary of the shear cell device. Simulation conditions were pure Al (c_0 = 0 at.%) and the temperature gradient was set according to the temperature measurement as shown in **Fig. 1** (ii). To visualize the convection behavior during the diffusion experiment, Fick's law equations, Navier-Stokes equations, and energy balance equations were solved.

3. Results

Experimental results using the shear cell method have already been published in reference 3). **Figure 1** (iv) shows the CFD results of the velocity field. The maximum absolute velocity at the bottom (x_1~x_{10}) of the gravity direction was 1.93×10^{-14} ms^{-1} and the maximum absolute velocity at the top (x_{11}~x_{20}) was 8.22×10^{-14} ms^{-1}.

Therefore, a stable density layering was observed and convection was suppressed at the bottom. On the other hand, the density layering was not stable at the top, and convection occurred.

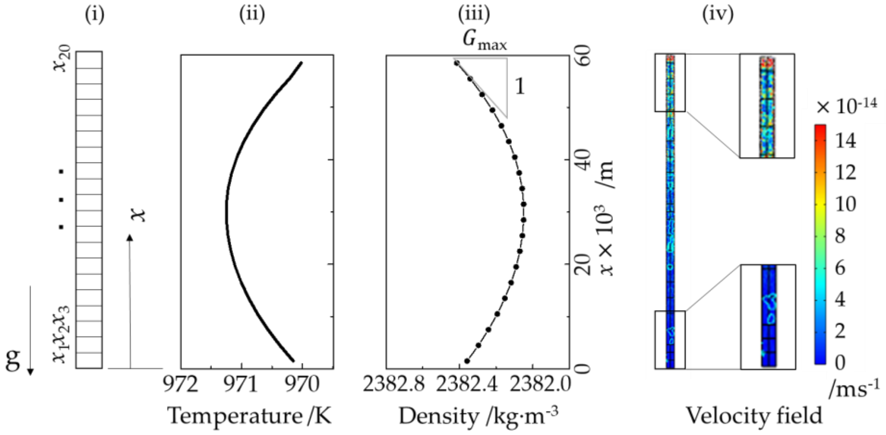

Figure 1. Conditions and results of simulation reproduced a shear cell experiment (Simulation conditions were pure Al (c_0 = 0 at.%)). (i) Schematic diagram of a capillary in a shear cell device, (ii) Temperature distribution, (iii) Density distribution in the initial state, and (iv) Velocity field of pure Al in the capillary.

4. Discussion

The calculation method of the maximum value of the density gradient G_{max} is demonstrated in Eq. (1) [2] and **Fig. 2**, which shows the results of Cap. B as an example.

$$G_{max} = max\left[\frac{\rho_{i+1} - \rho_{i-1}}{2\Delta x}\right] \tag{1}$$

Rayleigh number was calculated by Eq. (2) [4,5],

$$Ra = \frac{gr^4}{\eta D} G_{max} \tag{2}$$

where r is a capillary radius (7.5×10^{-4} m), g is gravitational acceleration (9.8 m/s^2), η is the viscosity of pure Al (1.29×10^{-3} Pa·s) [6], and D is the diffusion coefficient of Sn in liquid Al which is measured by shear cell technique (6.7×10^{-9} m^2/s). The *Ra* at the beginning and the end of the experiment for each capillary is shown in **Fig. 3**. For small initial concentrations (Cap. A and B), *Ra* increased with time. It is suggested that convection due to a slight temperature gradient, which generated in pure Al, occurred initially in the initial states and was not suppressed. On the other hand, for large initial concentrations (Cap. C and D), *Ra* decreased with time. Therefore, accurate experiments can be performed under experimental conditions where *Ra* decreases during diffusion experiments.

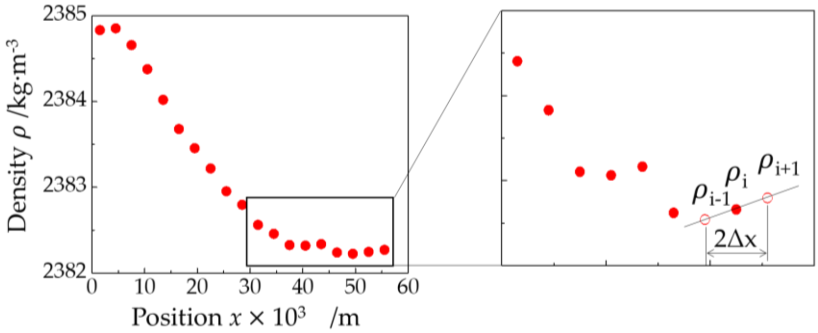

Figure 2. Density distribution of Cap. B (The initial concentration of Sn c_0 = 0.46 at.%) and the method to calculate the density gradient.

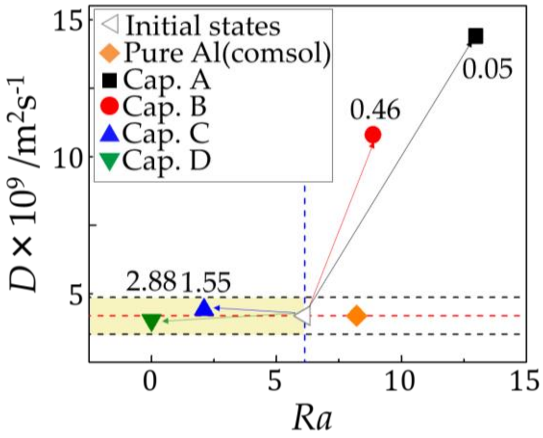

Figure 3. Relationship between Rayleigh number (*Ra*) and the diffusion coefficient of Sn in liquid Al (*D*). The number next to the plot is the initial concentration of Sn (c_0).

5. Conclusion

The natural convection can be suppressed when the Rayleigh number (*Ra*) decreases during the diffusion experiment.

Acknowledgment

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