CHAPTER 1

Application of a Magnetic Field for Material Processing

The convection of liquid metal under the influence of a magnetic field has been studied extensively. Early research results are described in a book by Chandrasekhar [1]. Pioneering studies on the effect of a magnetic field on the convection of electro-conducting materials were basically carried out in the fields of the geophysics and cosmology and were related to convection of the Earth's mantle or of gas in a space [2]. In industry, on the other hand, the application of a magnetic field in the convection of *liquid metal* appears to be a recent development. Applications include convection control for the *molten silicon* in the crucible of the *Czochralski crystal-growing* process, convection of molten steel in a *continuous steel-casting* process, and liquid metal cooling in a *nuclear reactor*.

The present book describes the convection of liquid metal affected by a *Lorentz force* in the first 14 chapters, and the convection of weakly magnetic materials due to *magnetic* (or magnetizing) *force* in a strong magnetic field in the later chapters.

Chapter 2 deals with the convection of liquid metal in a shallow layer that is heated from below and cooled from above, i.e., *Rayleigh-Bénard* convection and its oscillatory characteristics. In chapter 3, the magnetic field is applied in the natural convection of liquid metal either vertically or horizontally, and a two-dimensional flow field is studied. In chapter 4, a three-dimensional numerical model system is studied for liquid metal in a cubic enclosure heated and cooled from opposing vertical side-walls without and with a magnetic field. The application of a magnetic field to liquid metal usually results in the suppression of convection due to a Lorentz force. However, the experimental results suggested an *enhancing effect*, and this effect is studied in chapter 5. In chapter 6, the *Seebeck effect* is considered for natural convection in a cubic enclosure with its possible application in a *dendrite solidification* system. These numerical approaches are applied to a Czochralski crystal-growing system without and with a magnetic field. Chapters 7 and 8 present flow visualization for silicon oil in a Czochralski crucible without a magnetic field, while chapter 9 considers further the cooling effect from the free surface. Next, the application in a Czochralski system of either a *vertical* (chapter 10), *transversal* (chapter 11) or *cusp-shaped* (chapter 12) *magnetic field* is considered, and a *rotating magnetic field* is studied for a vertical cylindrical melt layer in chapter 13. Lastly, inasmuch as the magnetic field acts on liquid metal due to a Lorentz force, the *continuous steel-casting* system is studied with various directional magnetic fields in chapter 14.

From 1986 or after, *super-conducting materials* at high temperature (about 90 K or so) had been invented and super-conducting magnets became more widely available for laboratory use. In 1991, de Rango *et al.* [3] reported levitation of non-ferrous materials, while Braithewaite *et al.* [4] reported the enhancement or cancellation of gravitational convection due to a magnetic field for a solution of *gadolinium nitrate* in a shallow layer heated from below and cooled from above. The later chapters of this book deal with the effects of magnetizing force on air and water. Simple mathematical model equations are derived in a similar way to the usual *Boussinesq approximation* for both temperature variation or concentration variation. In chapter 15, the stably stratified air in a cube heated from above and cooled from below is disturbed by the magnetic field of four pole magnets located outside the cube. Chapter 16 considers a shallow layer of air heated from below and cooled from above, while chapter 17 examines the effects of various parameters. Chapter 18 describes the convection and diffusion of oxygen gas in a vertical glass tube located in a super-conducting magnet, and examines the effect of *concentration* of oxygen gas in nitrogen gas due to a strong magnetic field on the convection. Chapter 19 turns to the Rayleigh-Benard convection of water rather than air, and chapter 20 studies numerically the *magnetothermal wind tunnel* reported by Uetake *et al.* [5].

References

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3. de Rango P., Lee M., Lejay P., Sulpice, Tournier R., Ingold M., Germi P. and Pernet M., *Nature*, **349** (1991), 770.
4. Braithwaite D., Beaugnon E. and Tournier R., *Nature*, **354**-14 (1991), 134-136.
5. Uetake H. *et al.*, *J. Appl. Physics*, **85**-8 (1999), 5735-5737.