Effects of Applied Power on Temperature of Electromagnetic Levitation of Silicon and Silicon-Iron Droplets

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Abstract. In this paper, a technique for non-conductive silicon heating and conductive silicon levitation is described. This research focuses on studying the effect of applied power on temperature of droplets during phosphorus removal from Silicon and ferrosilicon alloys (24%Fe-76%Si) by utilizing a refining process known as electromagnetic levitation with subjecting the levitated alloy to an argon-hydrogen gas flow. The effects applied power on temperature were observed and analyzed. The results of this investigation will use vacuum electromagnetic levitation technology solar grade silicon samples will be prepared from relative inexpensive raw material, metallurgical grade silicon.

1. Introduction
The electromagnetic levitation technology was first introduced in 1923[1]. The electromagnetic levitation (EML) furnace technology has a long history, and people have performed many metallurgical experiments with it. Today, the EML are used to assist experiments on melting, purifying, undercooling, and measuring properties, such as removing phosphorus from metallurgical grade silicon or ferrosilicon using EML method to provide solar photovoltaic industry with low cost silicon materials, hence bring the cost of solar energy down. At present, an expensive grade of silicon for semiconductor is used for solar cell to convert solar energy into electricity. The use of expensive raw material for photovoltaic industry results in a high cost of photovoltaic electricity, the cost of which is five-time higher than that of the electricity from conventional electricity generation[2-4]. To upgrade metallurgical silicon to solar grade silicon, a great number of research works have been carried out in this field of using relative inexpensive raw material, metallurgical grade silicon, as a starting materials for the production of solar grade silicon is one of the most economical way to make solar cells [1-6]. Solidification refining is an effective way to remove most impurities in molten silicon, which doesn’t need any chemical reaction, with the exception of phosphorus and boron[7-11].

This research focuses on studying the effect of applied power on temperature of droplets during phosphorus removal from Silicon and ferrosilicon alloys (24%Fe-76%Si) by utilizing a refining process known as electromagnetic levitation with subjecting the levitated alloy to an argon-hydrogen gas flow. In
this research the effects of applied power on the temperature were observed and analyzed, because dephosphorization from metallurgical grade silicon and ferrosilicon by vacuum electromagnetic levitation had been studied by the National Natural Science Foundation of China (Project No. 51664036). The results of this investigation will ultimately contribute to the body of research involving the development of feasible processes enabling the economic production of SoG-Si. Achieve quantificational characterization of microstructure and dephosphorization from metallurgical grade silicon and ferrosilicon by vacuum electromagnetic levitation will be achieved in order to explore the rule of how to control dephosphorization, which will promote the development the theoretical model and experimental basis for the application of technology.

2. Theoretical analysis

2.1. The heating Mechanism of the EML

Figure 1 below depicts the principle of electromagnetic levitation. Levitation coil design for levitation melting is essential to provide adequate lifting force, induction heating, and droplet stability.

![Figure 1. EML Principle](image)

The generator of the EML generates a non-uniform high frequency alternating current passes through the levitation coil with subjecting the levitated alloy to an argon-hydrogen gas flow[1]. When a conductive sample such as iron is placed in between the non-uniform, high frequency electromagnetic field generated by the levitation coil, the eddy current [10] is induced on the material surface. The eddy current than generate heat according to the relationship:

\[
H = I^2 R
\]

Where H is the heat; I is the current density; and R is the electrical resistance. Normally, the eddy current will flow at a direction opposite to the current flow direction of the levitation coil. It will also generate its own field in opposition to the field generated by the coil and thereby prevent the field from penetrating to the center of the sample.

2.2. The levitation Mechanism of the EML

A conductor can be made to levitate by balancing the electromagnetic body force (Lorentz force) and the gravity force which can be described using the governing equation [7]:

\[
J \times B = \rho g
\]

where J is the eddy current induced by the alternating magnetic field B, \( \rho \) is the density of the levitated material and g is the gravitational constant. The penetration depth of the eddy current, d, is given by [10]:

\[
d = \frac{\mu_0 B}{\rho}
\]
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\[ d = \frac{\rho}{\pi \mu_0 \mu_f f} \]  

(3)

Where \( \rho \) is the resistivity of the sample; \( \mu_0 \) is the magnetic permeability of the vacuum; \( \mu \) is the relative magnetic permeability of the sample; and \( f \) is the frequency of the alternating current. According to the above relation the higher the frequency the thinner or more shallow the heating. On the same time, the interaction between the eddy currents and applied field will generate a lifting force to hold the sample [1]. When the currents in the upper and lower coils flow in opposite directions, a field is produced in which the magnetic field is zero at the center point between the coils and increases in every direction outward. This magnetic well is capable of supporting the sample in the space without contacting any holder.

3. Results and discussions

3.1. Specimen preparation

The silicon specimens used in the preliminary levitation trials as well as in the future experiments are commercially available metallurgical grade silicon and ferrosilicon with manufacturer’s analysis shown in Table 1.

In this research, all the samples were provided by the Kunming Steel. In order to insert these samples into the levitation furnace, they were sliced into smaller cylinders. In theory, the sample for electromagnetic levitation furnace should be nearly spherical so the electromagnetic field will act on surface evenly. But it was too difficult to cut samples into spherical samples.

| Element                        | Si   | F   | P  | Ca  | S  | C   |
|-------------------------------|------|-----|----|-----|----|-----|
| Content of metallurgical grade silicon | 98%  | 0.5%| 0.004% | 0.1% | -  | -   |
| Content of Ferrosilicon       | 76%  | balance | 0.04% | -  | 0.02% | 0.2% |

3.2. Experimental conditions

The EML generates a non-uniform high frequency alternating current passes through the levitation coil with subjecting the levitated alloy to an argon-hydrogen gas flow. Experimental conditions: specimen weigh is 0.6-1g, frequency is 280KHz, applied power is 0.8KW-2.2KW, refining time is 1-8 minutes, Refining temperature is 400°C-1720°C, H₂-Ar gas composition is 0%H₂-Ar bal. to 100% H₂, Gas flow rate is 0.25-1.2 L/min, Iron alloying in Si-Fe is 24%Fe-76%Si, and initial phosphorus concentration is 60-500 ppm.

3.3. The effects of applied Power on levitation temperature of droplet

Droplet temperature measurement by immersed thermocouple is not permissible due to the small volume of the melt. Therefore non-contact technique such as infrared (IR) pyrometry must be used. Temperature measurements using an IR pyrometer and droplet temperature regulation via a proportional–integral–derivative (PID) controller are discussed in the following sections. The magnitude of power applied to the coil controls the vertical position of the droplet within the electromagnetic field, which, in turn determines the density of electromagnetic field lines that interact with the droplet[11]. The effects of input power on levitation temperature analysis shown in Figure 2. The effect of applied power on droplet heating behavior is shown in Figure 9.
By decreasing the power supplied to the coil, the lifting force is reduced and the droplet is located lower within the bottom coil, where the field flux is higher. As a result, the droplet temperature increases [11]. Conversely, by increasing power to the coil, the droplet sits higher within the electromagnetic field where the flux is weaker and consequently lower temperatures are achieved [11]. However, upon reaching a minimum temperature, further increase in applied power will lift the droplet higher into the electromagnetic field associated with the upper coil where the flux is greater and this will cause the droplet temperature to increase again, as shown in Figure 2.

3.4. The effects of time on levitation temperature of droplet

The effects of levitation time on temperature analysis shown in Table 2 and Table 3. The increase in heating rate at approximately 2 minutes is attributed to the silicon responding to the applied field and beginning to generate heat by induction.

| Table 2. The effects of levitation time on temperature analysis at 2.2KW |
|-------------------------------|---|---|---|---|---|---|---|
| Time/Min                     | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| Temperature /K               | 680 | 1500 | 1550 | 1600 | 1600 | 1580 | 1590 |

| Table 3. The effects of levitation time on temperature analysis at 0.8KW |
|-------------------------------|---|---|---|---|---|---|---|
| Time/Min                     | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| Temperature /K               | 400 | 500 | 630 | 700 | 780 | 1200 | 1700 |

4. Conclusion

(1) The EML generates a non-uniform high frequency alternating current passes through the levitation coil with subjecting the levitated alloy to an argon-hydrogen gas flow. When the currents in the upper and lower coils flow in opposite directions, a field is produced in which the magnetic field is zero at the center point between the coils and increases in every direction outward. This magnetic well is capable of supporting the sample in the space without contacting any holder.

(2) By decreasing the power supplied to the coil, the lifting force is reduced and the droplet is located lower within the bottom coil, where the field flux is higher. As a result, the droplet temperature increases. Conversely, by increasing power to the coil, the droplet sits higher within the electromagnetic field where the flux is weaker and consequently lower temperatures are achieved. However, upon reaching a minimum temperature, further increase in applied power will lift the droplet higher into the electromagnetic field.
electromagnetic field associated with the upper coil where the flux is greater and this will cause the droplet temperature to increase again.

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**References**

[1] Gao L, Shi Z, Li D H, Zhang G F, Yang Y D 2015 Applications of Electromagnetic Levitation and Development of Mathematical Models: A Review of the Last 15 Years *Metallurgical and Materials Transactions B*. Vol 47B pp 537-547

[2] Ikeda T and Maeda M 1992 Purification of metallurgical silicon for solar-grade silicon by electron beam button melting *ISIJ Int*. Vol 32 pp 635-642

[3] Ueda S, Morita K and Sano N 1997 Thermodynamics of phosphorus in molten Si-Fe and Si-Mn alloys *Metall. Mater. Trans. B*. Vol 28B pp 1151-1155

[4] Yoshikawa T and Morita K 2003 Removal of phosphorus by the solidification refining with Si-Al melts *Science and Technology of Advanced Materials* Vol 4 pp 531-537.

[5] Morita K and Miki T 2003 Thermodynamics of solar-grade silicon refining *Intermetallics* Vol 11 pp 1111-1117

[6] Wei K X, Ma W H, Dai Y N, Yang B, Liu D C and Wang J F 2007 Vacuum distillation refining of metallurgical grade silicon (I) - Thermodynamics on removal of phosphorus from metallurgical grade silicon *Trans. Nonferrous Soc. China*, Vol 17 pp 1022-1025

[7] Kubaschewski O and Alcock C B 1979 *Metallurgical Thermochemistry* 5th ed (Oxford, Pergamon Press) pp 80-94.

[8] Suzuki K, Kumagai T and Sano N 1992 Removal of Boron from metallurgical-grade silicon by applying the plasma treatment *ISIJ International* Vol 32 No.5 pp 630-634

[9] Teixeira L A V and Morita K 2009 Removal of boron from molten silicon using CaO-SiO\textsubscript{2} based slags *ISIJ International* Vol 49 No.6 pp 783-787

[10] Miki T, Morida K and Sano N 1996 Thermodynamics of phosphorus in molten silicon *Metall. Mater. Trans. B*. Vol 27B pp 937-941

[11] Wu P, Yang Y D, Barati M and McLean A 2014 Electromagnetic Levitation of Silicon and Silicon-Iron Alloy Droplets *High Temp*. DOI 10.1515/htmp-2013-0102, pp 1-5

[12] Pires J C S, Otubo J, Braga A F B and Mei P R 2006 The purification of metallurgical grade silicon by electron beam melting *Materials Processing Technology* Vol 169 pp 16-20