Short Communication

Coil Design for Lower Temperature Levitation Melting of Iron Alloys

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ABSTRACT

Numerous coil geometries were designed by trial and error, and it was found that the temperature of a levitated liquid iron alloy droplet can be maintained below 1350°C. To produce a lower temperature in levitation melting, the magnetic field should have a large gradient but a low strength. The lower temperatures can be obtained by smaller diameter of bottom turns, more bottom turns in a short distance, better electrical conductivity of coil, smaller separation between top and bottom turns, higher power, larger droplet and better electrical conductivity droplet.

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Levitation melting was proposed first by Much /1/ in 1923 and the theory /2,3/ of levitation in an electromagnetic field has been developed subsequently. Application of the levitation technique for melting of metals was studied beginning in the early 1950s /4-8/. Since 1960, levitation melting technology has been extensively used in studies of gas-metal or slag-metal reactions /9-19/, and molten metal densities /20,21/ for liquid iron alloys because it has the advantage of no ceramic contact. However, due to the lower electrical conductivity of molten iron based alloys, there have been problems with temperature control, which result in a near absence of experimental studies at lower temperatures for iron alloys as seen in Table 1. Recently, a cold crucible method /22,23/ was applied with levitation melting for pouring a molten charge, where the temperature can be below the melting point of the iron based metal. But this method is difficult for the purpose of metallurgical reaction studies because the cold crucible would affect the reaction gas flow around the liquid sphere and the turbulence or spark emission due to the targeted reaction would damage the crucible and prevent a quantitative study. Because experimental levitation investigations were limited to higher temperatures, studies of reaction mechanisms were unable to reproduce many reaction phenomena at lower temperatures as the situations in practical processes, such as direct iron making processes, blast furnace or the scrap melting processes. In recent studies /24-27/, the authors have investigated gas-metal reactions at lower melt temperatures representative of commercial cast iron melting conditions. This necessitated a new approach to levitation coil design. In the present work, numerous coil geometries were designed by trial and error, and it was found that the temperature of a levitated iron alloy droplet can be maintained below 1350°C without using a higher flowrate of cooling carrier gas, such as helium. The temperature of a levitated droplet could be measured to within ±15°C under these conditions.

Table 1
Previous work on levitation melting of iron alloys

Investigators	Ref.	Study	Temperature range (°C)
Baker	9	G/M	1600
Distin et al.	10	G/M	1750-1800
Wada et al.	11	G/M	1800-2100
Knights and Perkins	12	S/M	1600-2000
Sano and Matsushita	13	G/M	1550-1800
Vig and Lu	14	G/M	1638-1775
Greenberg and Mclean	15	G/M	1540-1650
Radzilowski and Pehlke	16	G/M	1600
Ito et al.	17	G/M	1800-2100
Robertson and Jenkins	18	G/M	1600-2800
El-Kaddah and Robertson	19	G/M	1650
Saito and Sakuma	20	Density	1800-2100
Adachi et al.	21	Density	1550-1700

G/M: gas/iron alloy reaction
S/M: slag/iron alloy reaction
Density: iron alloy density

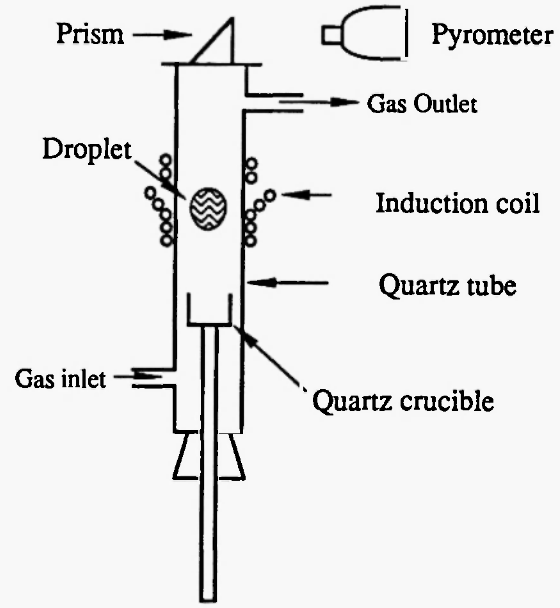

Fig. 1: Levitation unit.

Briefly, levitation of a metal occurs when a diverging electromagnetic field is used to induce current in the conducting material placed within a water-cooled metallic coil. The field is produced by a high frequency AC current in a suitably shaped coil. Induced eddy currents interact with the magnetic field to produce body forces. These forces act from the surface to the bulk of the droplet. The integral of the forces results in the movement of the droplet. Assuming the system is symmetrical in the horizontal direction, the forces may levitate or push the droplet down. For a cone shaped coil, if the droplet is within the cone, the resulting forces levitate the droplet.

The coil designs were tested using a quartz tube (O.D. 15, 15-12 and 15-9 mm), shown in Figures 1 and 2, with a gas inlet in the lower section and an outlet in the upper section. The top of the tube was closed with a prism mounted on an optical flat. Temperature was measured using a pyrometer viewing the upper surface of the droplet. Hydrogen was used to purge the reaction tube to deoxidize any oxide layer present on the surface of the droplet. Hydrogen was then replaced by helium gas at a low flowrate of 50 ml/min during the temperature measurement. The coil (copper tubing, ϕ 3.0 mm O.D.) for levitation is mounted outside of the reaction tube. The power supply was a 23.5 kW generator having a frequency of 375 kHz (Lepel, Model T-10-3). Between the generator and the levitation coil, there is a 7:1 step down transformer (Lepel, Model LC.T.-4). The typical composition of a one gram iron alloy sample was 3.5 wt% carbon. 2.0 wt% silicon, 0.36 wt% manganese and 0.05 wt% sulfur.

Several experimental observations were made based on the tests with various coil designs. On melting, the specimen sometimes became unstable and touched the tube wall. To prevent this, the starting sample should be nearly spherical in shape, and once it is levitated, the power must be reduced to allow the sample to fall into the high temperature zone for fast melting. Sometimes the droplet moved closer to the wall because the field on the opposite side was strong. The droplet had a tendency to be pushed from the stronger part of the field to the weaker part of the field. The asymmetrical field distribution may have been due to non-symmetry in the coil and also if the droplet was not symmetrical. The droplet could be moved back towards the center by a) bringing the distance between the coil at the region closer; this increases the magnetic flux density at the point and also increases the horizontal forces, or b) increasing the distance between the coil, diametrically opposite, which

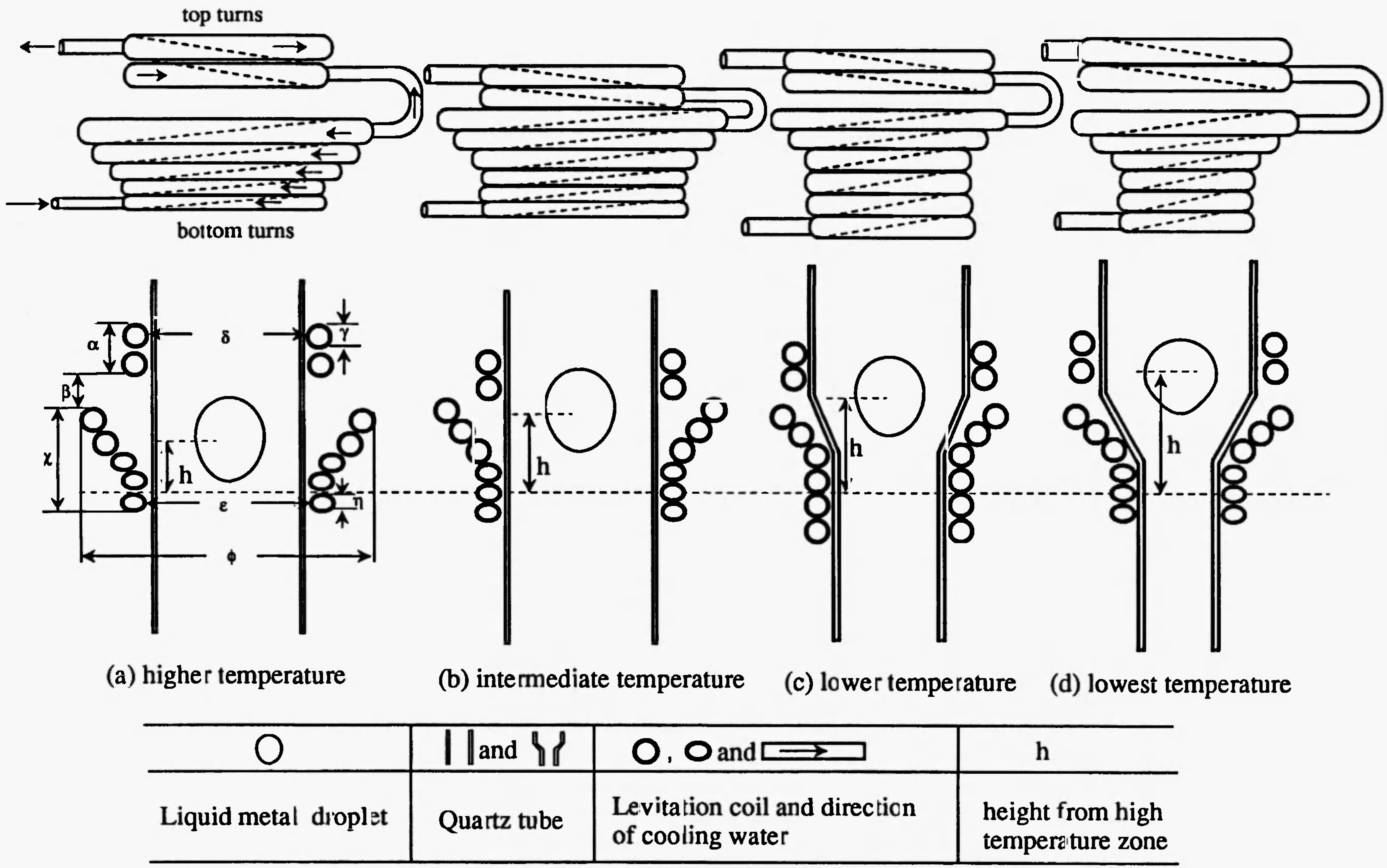

Fig. 2: Schematic drawing of levitated metal droplet.

would act in the opposite sense as above. Interaction of the liquid velocity (fluid movement within the droplet) with the magnetic field will result in non linear body forces (**v** × **B**). These non linear body forces result in the spin of the droplet about its vertical axis, as frequently observed once the droplet is melted.

A larger sample is easier to levitate than a smaller sample because the induced current tends to flow between the skin depth of the droplet surface, and the stronger the induced current within the sample, the stronger the magnetic field which produces a greater levitation force. Materials with higher electrical conductivities are easier to levitate because the induced current is strong, and lower temperatures can be reached. For example, at the same levitation condition for a copper sample, the temperature is about 500-800°C, while for an iron sample, the temperature is 1550-1700°C. In order to obtain a stronger levitation force, more turns must be made in a short distance, so the copper tubing was also flattened (~2.5-2.6 mm thickness) for the bottom turns. The smaller the diameter of bottom turns, the stronger the levitation force. Increasing the separation between the top and bottom turns and decreasing the power input will increase the temperature of the droplet. The temperature of the droplet is controlled to within ±15°C by changes of this separation and by changing the power for a fine adjustment.

Using the following methods, lower temperatures can be obtained with a stronger levitation force, whereby the droplet is forced to a higher location within a lower temperature zone.

- smaller diameter of bottom turns
- more bottom turns in a short distance
- better electrical conductivity of coil
- smaller separation between top and bottom turns
- higher power
- larger droplet
- better electrical conductivity droplet

Figure 2 shows various coil geometries designed for iron alloys in the temperature range of 1350°C-1700°C based on the foregoing descriptions. Table 2 gives their dimensions. Figure 2a, b, c and d shows the coil geometries used for higher (>1700°C), intermediate (1550-1700°C), lower (1450-1550°C) and lowest (<1450°C) temperature melting, respectively. The separation between the top and bottom turns of the higher temperature coil is relatively large. For relatively low temperature melting, there are more bottom turns of smaller diameter and the levitation force is stronger. A visual observation shows that the heights from high temperature zone, h, in Figure 2, were increased in the order of higher, intermediate, lower and lowest temperature melting. About one gram of cast iron can be successfully levitated at temperatures below 1350°C using coil geometries for lowest temperature melting (Figure 2d). However, the temperature of the metal sample fluctuated wildly if the temperature of the metal sample was at or below the liquidus temperature. This phenomenon is due either to the great difference in electrical conductivity of the solid and liquid of the metal, or to the asymmetrical shape of the half melted droplet.

The shape of the droplet will alter the magnetic field distribution, and consequently, the Lorentz force distribution within the droplet will change. Thus the droplet will have different shapes at different positions of levitation. The surface tension and density of the liquid, which have temperature dependencies, are believed to affect the equilibrium shape of the droplet as

Table 2

Dimensions of coils

Coil for the melting temperature of	α	β	χ	δ mm	ε	φ	γ	η
a,higher >1700°C	7	2-4	18	16	16	30	3	2.5
b,intermediate 1550-1700°C	6	-1-2	20	15	15	30	3	2.5
c,lower 1450-1550°C	6	1-3	25	16	12	28	3	3.0
d,lowest <1450°C	7	1-3	20	15	9	25	3	2.5

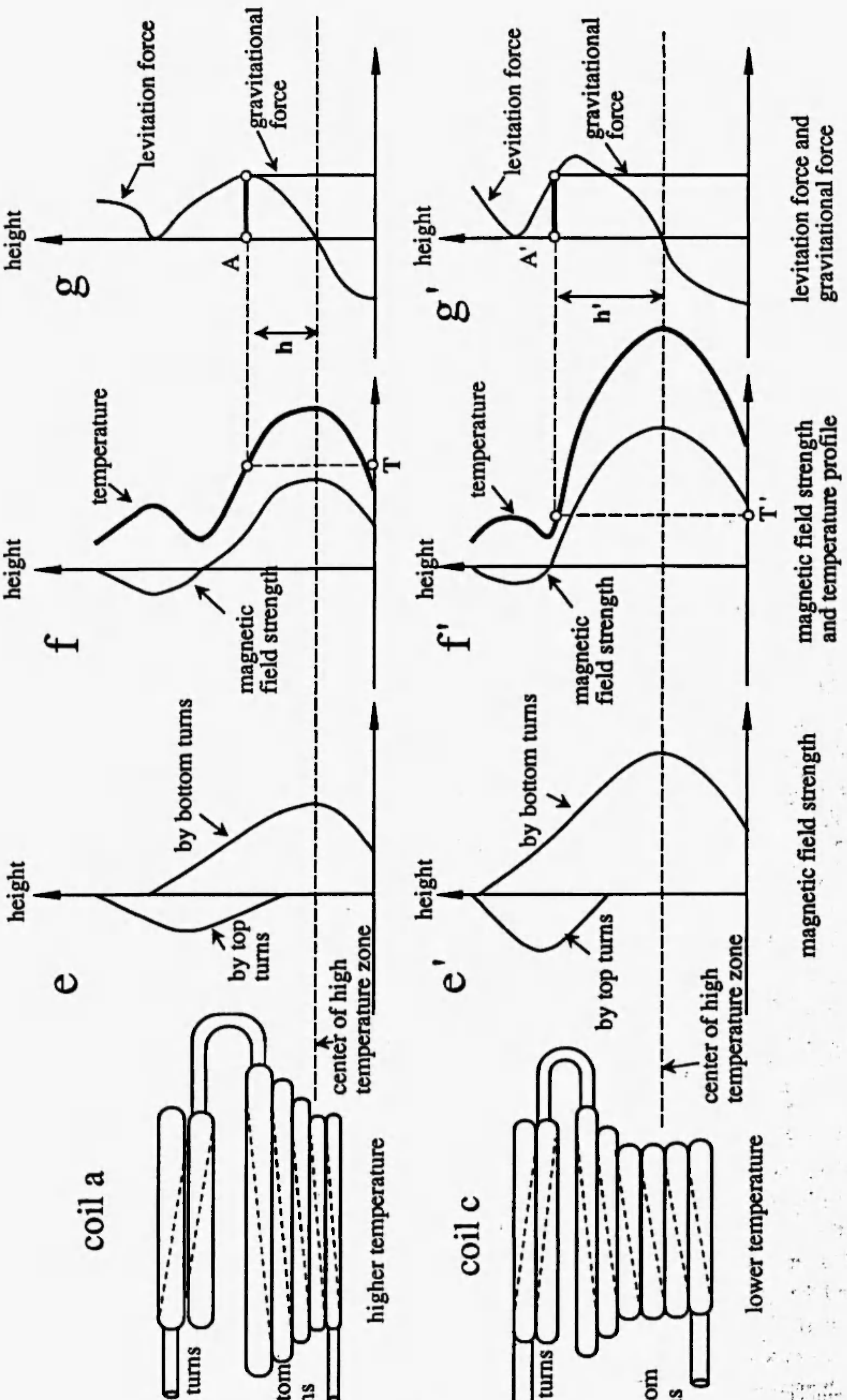

Fig. 3: Effect of coil geometry on levitation characteristics.

well. The droplet shape in each coil design, observed during melting, is roughly shown in Figure 2. The length of the vertical axis of the droplet tends to decrease in the lower levitation temperature coil.

Figure 3 presents the effects of coil geometry on levitation characteristics for coils a and c. Coils a and c are the coil geometries for higher and lower temperature melting. The main differences between them are: larger diameter of bottom turns, larger separation between top and bottom turns and fewer bottom turns for a than c. Based on magnetic field measurements for several coil geometries by Fromm and Jehn /8/, Figures 3e and 3e′ give the strength of magnetic field produced by top and bottom turns separately. The field produced by the bottom turns in Figure 3e′ is stronger than that in Figure 3 because of the smaller diameter and more bottom turns for coil c than for coil a. For the top turns, since the distance between turns is shorter for coil c ($\alpha = 6$ mm) than for coil a ($\alpha = 7$ mm), the field produced by the top turns of coil c is also stronger than that of coil a. Figures 3f and 3f′ show the field profiles of coils a and c, respectively, representing the offset of the magnetic field produced by lower turns with that by upper turns. The temperature profiles in Figures 3f and 3f′ are based on the field strength and the assumption that the droplet is located at the point shown. This shape of the temperature profile was also experimentally observed using 1 gram of metal held in a quartz crucible placed at various heights as shown in Figure 1. The levitation forces produced by the gradient of the field strength are shown in Figures 3g and 3g′. A stronger force is shown in Figure 3g′ than in Figure 3g because of the larger gradient of field strength due to a stronger field from the bottom turns and the opposing field of top turns for coil c. The droplet is stable at points A and A′ where the gravitational force of the droplet is equal to the levitation force. The temperature of the droplet is then T or T′, where $T' < T$ and $h < h'$ as seen in Figures 3f, 3f′, 3g and 3g′, i.e., a lower temperature can be obtained by coil c than coil a.

The different shape of the droplet in coil and coil c is believed to be due to the gradients of the levitation forces of the two coils, as seen in Figures 3g and 3g′. The levitation force of coil a has a gentle slope in the vertical direction compared with the steep one of coil c, which allows a longer vertical axis of the droplet in coil a than in coil c.

In summary, to produce a lower temperature in levitation melting, the magnetic field should have a large gradient but a low strength.

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