Behaviour of Cavity Formation and Convection in FeOx–SiO₂ Melts under Plasma Arc

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The behaviour of oxides melted by plasma arc has been studied. Oxides of FeOx and FeOx–SiO₂ were melted by argon plasma arc. A direct-current-transferred-type plasma generator was employed. Observations of the sample surface revealed that a cavity formed in the region where the plasma arc was directed and that surface flow was operative in the direction from the centre toward the edge of the melt. The depth of the cavity was governed by the balance between the hydrostatic pressure and the sum of the pressures caused by the arc and the argon gas flow. The main driving force of convection on the sample surface was the aerodynamic drag force. The temperature distribution was dependent on both the argon gas flow rate and the viscosity of the sample, because the heat from the plasma arc was mostly transported by convection on the sample surface.

KEY WORDS: silicate glasses; iron oxide; plasma arc melting; cavity formation; convection; temperature distribution.

1. Introduction

In Japan, about 70% of municipal solid wastes are burned in incinerators. Ashes produced from incineration are of low density and contain leachable toxic chemicals such as heavy metals. The majority of ashes are currently disposed of to landfills. However, this situation will not be sustainable due to the shortage of suitable landfill sites and the introduction of more stringent environmental dumping legislation.

A vitrification process by plasma arc is one of the promising solutions, to reduce the volume of the ashes and to decrease its influence on environment.^{1–4)} It has been expected that the ashes can be converted to high quality glasses such as substitutes for marble or granite building materials through plasma arc vitrification. However, the evaporation of the heavy metals from the ashes to change non-toxic glasses is strongly affected by convection and temperature distribution during plasma arc vitrification. To establish the effective vitrification process, knowledge of the convection mode and the temperature distribution of ashes melted by plasma arc has been required.

As far as the authors known, there are few fundamental studies on molten glasses melted by plasma arc.⁵⁾ In several previous studies, it has been reported that when the synthetic incinerator ashes were melted by argon plasma arc, the cavity formed on the surface of the molten ashes under the plasma arc and the direction of

convection on the surface was that from the centre to the edge of the melt. It was also found that the temperature near the centre of the melt reached about 2200 K, which was about 330 K higher than that at the edge. There is no discussion on the influence of plasma arc on the behaviour of molten glasses such as the formation of cavity, the convection mode and the temperature distribution on the surface of the melt.

The aim of this study is to understand factors affecting the cavity formation and convection in molten oxides under plasma arc. In the present work, FeOx and FeOx–SiO₂ are used as the melting samples, since the physicochemical properties of both systems have been well studied.⁶⁾ The formation of cavity is studied in terms of the arc current and the argon gas flow rate. The direction and velocity of convection on the sample surface are also investigated and discussed the influence on the temperature distribution.

2. Experimental

2.1. Plasma Arc Melting

Figure 1 shows a schematic diagram for the plasma generator. A direct current (DC) transferred type plasma generator was used with a tungsten cathode and a copper anode. Both electrodes were water-cooled. A copper mould (50 mm in diameter × 5 mm in length) was placed on the copper anode. The argon gas was always flown around the cathode and blew against the samples. The

Fig. 1. A schematic diagram for the plasma generator.

Table 1. Experimental conditions.

Amount of SiO ₂ (mass%)	10, 20, 30
Argon gas flow rate (Nm ³ /s)	0.5×10^{-4} – 2.0×10^{-4}
Arc current (A)	175, 200, 225
Arc length (mm)	25, 30, 35

chamber was made of stainless steel, also being water-cooled, and had view ports. A thermocouple was inserted into the chamber through one of the ports. A copper tube (6 mm in diameter) was equipped near the cathode to add MgO powder as a marker onto the melting samples.

Two kinds of samples were used in this study: FeOx (45 g) and FeOx–SiO₂ (45 g). The oxide of Fe₂O₃ and SiO₂ were used as initial materials and were pre-melted by argon arc plasma to shape into the copper mould. Since the partial pressure of oxygen in the chamber was about 10 Pa, the oxide of Fe₂O₃ was mostly reduced to FeOx during the cause of pre-melting. The DC plasma arc was ignited by a pilot arc sparked from the cathode using a high frequency starter and was generated between the tungsten cathode and the sample. Experimental conditions are summarised in Table 1. During melting argon gas (99.998 mass% purity) was supplied into the chamber and the flow rates were controlled using a mass flow controller. The arc current and arc length were kept constant during the experiment.

2.2. Influence of the Arc Current and the Argon Gas Flow Rate on the Formation of Cavity

To investigate the formation of the cavity in terms of the arc current and the argon gas flow rate, the arc current and the argon gas flow rate which formed the cavity with the depth of 5 mm were measured as follows: Firstly, the samples were mounted and melted in the copper so that the sample thickness was mould equal to the depth of the mould. During melting the sample, the arc current and arc length were kept constant. The argon gas flow rate was then gradually increased and it followed that the depth of the cavity progressively increased. The argon gas flow rate was recorded when the bottom of the cavity

reached the surface of the copper mould under the sample. This value was the minimum gas flow rate required for the maximum depth of the cavity.

2.3. Measurement of the Velocity of Convection on the Sample Surface

Particles of MgO (1 mm in diameter × 1 mm in length) were added onto the surface of the melting sample (50 mm in diameter) through the copper tube to observe convection on the surface. Views of the sample surface were recorded using a video camera and the velocity of convection on the sample surface was determined from the motion of the MgO particles. It was confirmed that the MgO particles were not melted in the sample during the observation.

2.4. Temperature Measurements on the Sample Surface

Surface temperatures of the molten samples were measured using a radiation thermometer. The radiation thermometer had a silicon photodiode as the detector, and measurements were carried out at a wavelength of 650 nm. The effective emissivity value required for the radiation thermometer was determined as follows: Firstly, the temperature near the edge of an FeOx sample was measured using a thermocouple of Pt·6mass%Rh–Pt·30%Rh. The temperature at the same position was then measured using the radiation thermometer, assuming that the effective emissivity was unity. Using these temperature values, the effective emissivity was derived from Wien's law of radiation,⁷⁾

$$\frac{1}{T} = \frac{1}{S} + \frac{\lambda}{C_2} \ln \varepsilon \quad \dots\dots\dots (1)$$

where T and S are the temperatures measured using the thermocouple and the radiation thermometer, respectively, λ the wavelength used for the radiation thermometer measurement, C_2 the Wien–Planck constant (1.43×10^{-2} m K), and ε is the effective emissivity. The estimated effective emissivity was 0.99 ± 0.01 for the FeOx samples. This calibration was made also on the FeOx–SiO₂ sample, resulting in the same value of the effective emissivity.

It has been reported that the values for various molten oxides are higher than 0.8.⁸⁾ Therefore, it is considered that the value of 0.99 obtained is acceptable as the effective emissivity for the temperature measurements in the present study. Consequently, the temperature distribution on the sample surface was measured using the radiation thermometer, assuming that the effective emissivity was independent of temperature. This assumption is considered to be reasonable, since it has been reported that the emissivity value for molten Al₂O₃ is almost constant at temperatures from its melting point ($\varepsilon = 0.97$) to 2 500 K ($\varepsilon = 0.95$).⁹⁾

3. Results and Discussion

3.1. FeOx Sample

3.1.1. Mechanism of Cavity Formation

Figure 2 shows an FeOx sample melted by plasma arc with an arc current of 175 A and an arc length of 30 mm. The FeOx sample seems to melt completely. During

Fig. 2. Surface of the FeOx sample melted by plasma arc.

Fig. 3. Relationship between the minimum argon gas flow rate and the arc current to form the cavity with the depth of 5 mm for the FeOx sample.

melting, the cavity appeared in the centre of the sample just under the plasma arc. As the argon gas flow rate increased, the depth of cavity progressively increased. When the gas flow rate was over $1.5 \times 10^{-4} \text{ Nm}^3/\text{s}$, the copper mould containing the sample was directly exposed to the plasma arc. This value was the minimum gas flow rate required for the maximum depth of the cavity with an arc current 175 A and an arc length of 30 mm.

Figure 3 shows the minimum argon gas flow rate as a function of the arc current to form the cavity with the depth of 5 mm for the FeOx sample. The vertical axis denotes the argon gas flow rate, w , under the standard condition (273 K, 101.3 kPa). As the arc current increases, the gas flow rate linearly decreases. While, the minimum gas flow rate required to form the cavity increases with increasing the arc length. The error bar represents the scatter in measured values. The scatter in the gas flow rate was $\pm 0.6 \times 10^{-5} \text{ Nm}^3/\text{s}$.

It is assumed that the arc pressure and the argon gas pressure are balanced with the hydrostatic pressure of molten oxides at the bottom of the cavity. The arc pressure (P_p) is equal to the Lorentz force related to the arc current¹⁰⁾:

$$P_p = \mu_0 I^2 / 4\pi^2 R^2 \quad \text{.....(2)}$$

where μ_0 is the magnetic permeability of vacuum, I the arc current, R the radius of the plasma arc column. The pressure caused by the argon gas flow (P_g) can be

Table 2. Radius of the arc column at arc current of 200 A and gas flow rate of $8.3 \times 10^{-5} \text{ Nm}^3/\text{s}$.

Arc length	Radius of the arc column
25 mm	3.0 mm
30 mm	3.5 mm
35 mm	4.0 mm

Fig. 4. Ratio of P_g to P_h as a function of the ratio of P_p to P_h .

expressed as¹¹⁾:

$$P_g = \rho_g w^2 / 2 \quad \text{.....(3)}$$

based upon Newton's second law of motion, where ρ_g is the density of argon gas. The hydrostatic pressure (P_h) is proportional to the density of the sample (ρ_l) and the depth of cavity (H):

$$P_h = \rho_l g H \quad \text{.....(4)}$$

where g is the acceleration due to gravity. The pressure yielded by the surface tension is neglected, assuming that the bottom of the cavity is flat. Therefore, the balance among the pressures at the bottom of the cavity is given by Eq. (5).

$$P_h = P_p + P_g \quad \text{.....(5)}$$

and the above equation can be rewritten as:

$$1 = P_p / P_h + P_g / P_h \quad \text{.....(6)}$$

The terms P_h , P_p and P_g can be calculated using Eqs. (2) through (4). The radius of the plasma arc column has been estimated from the photograph of the plasma arc column shot at the side port of the chamber. This photograph was taken at 1/8 000 s in shutter speed and 22 in aperture. Table 2 shows the radius of the plasma arc column at arc current of 200 A and gas flow rate of $8.3 \times 10^{-5} \text{ Nm}^3/\text{s}$. Argon gas is regarded as an ideal gas. Since there is temperature gradient between plasma and sample surface, the temperature of argon gas on the sample surface is assumed to be the same as that of the sample surface, 1700 K. The density of the FeOx sample is $4.5 \times 10^3 \text{ kg/m}^3$ at 1 673 K,¹²⁾ assuming that the densities do not change much in the temperature range of 1 673 K to 1 700 K.

Figure 4 shows the relation between the ratio of P_g to P_h and the ratio of P_p to P_h , which have been calculated using the argon gas flow rate and the arc current required to form the cavity with the depth of 5 mm. The line in

Fig. 5. Illustrative sketch of the MgO particles movement.

Fig. 4 represents by Eq. (6). As can be seen, all the calculated results agree with this line within reasonable experimental error.

In this study, it is assumed that the temperature of argon gas on the sample surface is the same as that of the sample surface. If typical temperature of the plasma, 10 000 K, is regarded as the argon gas temperature on the sample surface, the values of P_g calculated using Eq. (3) would be unreasonably larger than that of P_h required to form the cavity with the depth of 5 mm. Therefore, this assumption of the argon gas temperature is appropriate.

The values of the velocity of the argon gas, the density of the molten sample and the magnetic permeability of the plasma generally depend on the temperatures of argon gas or molten sample, which directly affects the calculation of the P_g , P_p and P_h . However, in the present study, the argon gas temperature may be assumed to be independent of both the arc current and the argon gas flow rate within the experimental conditions, since the sample surface temperature just under the plasma arc is almost independent of those factors. The effects of those factors on the sample surface temperature is discussed later in Sec. 3.1.3. Therefore, it is considered that the velocity of the argon gas, the density of the molten sample and the magnetic permeability of the plasma may not significantly affect the calculation plots in Fig. 4. Accordingly, it is concluded that the pressures required to form the cavity are equal to the sum of the arc pressure and the pressure caused by the argon gas flow.

3.1.2. Velocity of Convection on the Sample Surface

The motion of the MgO particles added to the sample surface was observed due to surface convection during arc melting. Figure 5 illustrates a sketch of the MgO particles movement. The direction of convection on the surface of the FeOx sample was always that from the centre to the edge on the surface. The average velocity of this convection was calculated from the motion of the MgO particles recorded using a video camera. Figure 6 shows the average velocity, V , on the surface of the FeOx sample as a function of the argon gas flow rate. It is obvious that as the argon gas flow rate increases, the average velocities of convection increase under various experimental conditions. The error bar represents the scatter in measured values. Then as gas flow rate increases, the depth of the cavity increases and temperature distribution on the sample surface changes, too.

Fig. 6. Average velocity of the FeOx sample surface as a function of the argon gas flow rate.

	Arc current	Arc length
○	175 A	25 mm
△	200 A	30 mm
□	225 A	35 mm
▲	200 A	30 mm
▼	200 A	30 mm

Fig. 7. Schematic illustration of convection due to each driving force.

It has been considered that the influence of temperature distribution of the plasma on the fusion behaviour requires further investigation.

Driving forces of convection on the sample surface under the plasma arc can be classified into four kinds of forces *i.e.*, the electromagnetic force, buoyancy force, force due to the difference in surface tension and aerodynamic drag force.¹³⁾ Figure 7 illustrates schematic diagrams of convection due to the four kinds of driving forces. Since FeOx whose electrical conductivity is about $2.0 \times 10^4 \Omega^{-1} \text{ m}^{-1}$ at 1 700 K,¹⁴⁾ being a good conductor of electricity. The electromagnetic force and the buoyancy force are operative inside the sample. The ratio of the electromagnetic force to the buoyancy force is given by Eq. (7).

$$R = \frac{g\Delta\rho}{\mu I^2 / \pi^2 a^3} \dots\dots\dots (7)$$

where $\Delta\rho$ is the difference in the density of the sample, μ the magnetic permeability ($1.26 \times 10^{-6} \text{ H m}^{-1}$) and a the radius of the anode region (2.5 mm). In the present study, $\Delta\rho$ is 238 kg m^{-3} ,¹⁵⁾ assuming that the difference in temperature between at the upper part and the lower part of the sample is about 400 K. Thus, the value of R

Fig. 8. Temperature distribution on the FeOx sample surface.

Arc current	Argon gas flow rate	
	$5.0 \times 10^{-5} \text{ Nm}^3/\text{s}$	$8.3 \times 10^{-5} \text{ Nm}^3/\text{s}$
175 A	●	○
200 A	▲	△
225 A	■	□

is calculated to be 0.007 from Eq. (7). Therefore, it is concluded that the electromagnetic force is stronger than the buoyancy force inside the sample and the direction of convection due to the electromagnetic force is opposite to that of convection observed experimentally.

On the other hand, the force due to the difference in surface tension and aerodynamic drag force are operative on the sample surface. Since the temperature coefficient of surface tension of FeOx is positive,¹⁶⁾ convection due to the difference in surface tension tends to be operative in the direction from the edge to the centre on the sample surface. Therefore, it can be considered that the aerodynamic drag force is the main driving force, resulting in convection in the direction from the centre to the edge on the sample surface.

3.1.3. Temperature Distribution on the Sample Surface

Figure 8 shows the temperature distribution on the FeOx sample surface, from the centre ($r=0$ mm) to the edge ($r=25$ mm). In the region of $r < 4$ mm, the temperature was not able to be measured accurately due to the formation of the cavity. Therefore, the temperature distribution except for this region has been presented in this figure. The scatter in the temperature value is estimated to be ± 15 K from the fluctuation in output signals of the radiation thermometer. The solid and dotted lines correspond to the argon gas flow rates of $8.3 \times 10^{-5} \text{ Nm}^3/\text{s}$ and $5.0 \times 10^{-5} \text{ Nm}^3/\text{s}$, respectively. In the region of $r > 14$ mm, as the argon gas flow rate increases, the temperature becomes higher. As the arc current increases, the temperature becomes higher at an argon gas flow rate of $5.0 \times 10^{-5} \text{ Nm}^3/\text{s}$. However, the arc current seems not to affect the temperature much at an argon gas flow rate of $8.3 \times 10^{-5} \text{ Nm}^3/\text{s}$. In the region of $r < 14$ mm, the temperature distribution is almost independent of both the arc current and the argon gas flow rate.

The output power of plasma arc was transferred to the anode by more than 80%.¹⁷⁾ The heat from plasma arc transported by three basic modes of heat transfer in the sample, *viz.*, conduction, convection and radiation.

 Fig. 9. Minimum gas flow rate for a cavity with the depth of 5 mm as a function of amount of SiO_2 at the arc length of 30 mm.

The energy of radiation (Q) can be calculated using the Stefan–Boltzmann equation which is given by Eq. (8).¹⁸⁾

$$Q = A\varepsilon\sigma T^4 \quad \dots\dots\dots(8)$$

where A is the area of the sample surface ($6.25 \times 10^{-4} \text{ m}^2$), ε the effective emissivity of the sample obtained (0.99), σ the Stefan–Boltzmann constant ($5.669 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$), T the average temperature on the sample surface, estimated as 1700 K. Using the above values, the energy of the radiation is estimated as 293 W from Eq. (8), which value is much smaller than the output power of plasma, 7000 W (200 A $\times$ 35 V). Therefore, the radiation heat transfer can be neglected compared with the conduction and convection heat transfer. The ratio of the conduction heat transfer to the convection heat transfer can be discussed based upon the Peclet number (Pe) given as¹⁹⁾:

$$\text{Pe} = v_1 r / k \quad \dots\dots\dots(9)$$

where v_1 is the velocity of convection on the FeOx sample surface, r the radius of the sample, k the thermal diffusivity of the FeOx sample. Generally, if the value of Pe is larger than 10, the conduction heat transfer is considered to be dominant. As for the FeOx sample melted by plasma arc, the average value of v_1 is 0.1 m/s as shown in Fig. 6 and r is 0.025 m. A value of k has been measured as $4 \times 10^{-7} \text{ m}^2/\text{s}$ by Ohta *et al.*²⁰⁾ Thus, the value of Pe is calculated to be 6000 from Eq. (9). It is, therefore, concluded that the heat from the plasma arc is mainly transported by convection on the sample surface and the temperature distribution is determined by convection on the sample surface. It has been considered that the value of Pe for glasses melted by plasma are greater than that for metals.

3.2. FeOx–SiO₂ Samples

3.2.1. Cavity Formation, Convection on the Surface and Temperature Distribution

Figure 9 shows the minimum gas flow rate required for the cavity with the depth of 5 mm as a function of the content of SiO_2 . During melting, the arc length was kept to be 30 mm. As the arc current or the content of SiO_2 increases, the minimum gas flow rate decreases.

Convection on the surface of the FeOx– SiO_2 samples was observed to be operative outward around the centre

Fig. 10. Illustrative sketch of the MgO particles movement.

 Fig. 11. Position of the borderline between the outward flow and inward flow as a function of the amount of SiO_2 at the arc current of 200 A and the arc length of 30 mm.

Argon gas flow rate
○ $5.0 \times 10^{-5} \text{ Nm}^3/\text{s}$
□ $6.7 \times 10^{-5} \text{ Nm}^3/\text{s}$
▽ $8.3 \times 10^{-5} \text{ Nm}^3/\text{s}$

of the sample, but no flow was observed near the edge of the sample, as schematically shown in Fig. 10. The dimension of the outward flow region was varied with the content of SiO_2 and the argon gas flow rate. Figure 11 shows the radius of the outward flow region as a function of the content of SiO_2 . During melting, the arc current was kept to be 200 A and the arc length was 30 mm. The position at $r=0$ mm corresponds to the centre of the samples. The dotted line represents the borderline of the outward flow. It has been found that the radius of the outward flow region becomes smaller as the SiO_2 content increases and the argon gas flow rate decreases.

Figure 12 shows the temperature distribution on the FeOx-SiO_2 sample surface. During melting, the arc current was kept to be 200 A, the arc length was 30 mm and the argon gas flow rate was $5.0 \times 10^{-5} \text{ Nm}^3/\text{s}$. The temperature decreases almost linearly with an increase in r for the $\text{FeOx-10mass\%SiO}_2$ sample. As the SiO_2 content increases, the temperature becomes lower at $10 \text{ mm} < r < 25 \text{ mm}$. The arrows denote the borderline of the outward flow shown in Fig. 11 for each content of SiO_2 . It seems that the temperature distributions depend on the dimension of the outward flow region.

 Fig. 12. Temperature distribution on the FeOx-SiO_2 sample surface at the arc current of 200 A and the arc length of 30 mm and the argon gas flow rate of $5.0 \times 10^{-5} \text{ m}^3/\text{s}$.

 Fig. 13. Relation between the value of $P_p + P_g$ and density of the sample.

3.2.2. Relation between the Cavity Formation and the Density of Samples

It is assumed that the balance among the pressures at the bottom of the cavity is given by $P_h = P_p + P_g$ for the FeOx-SiO_2 sample. In this equation, P_h is proportional to the density of the sample and the depth of cavity. Therefore, the value of $P_p + P_g$ would be dependent on the density of the sample. Figure 13 shows the relation between the value of $P_p + P_g$ and the density of the sample. The value of $P_p + P_g$ is calculated using Eqs. (2) and (3) on the same assumption as that used for the FeOx sample. The densities of the FeOx-SiO_2 samples at 1673 K have been cited from Slag Atlas.¹²⁾ Where, the physicochemical properties of the FeOx-SiO_2 system were used for FeOx-SiO_2 system saturated with iron. As the density of the FeOx-SiO_2 sample increases, the value of $P_p + P_g$ linearly increases. The slope of the straight line in this figure agrees with the product of the acceleration due to gravity and the depth of the cavity which was 5 mm.

Therefore, it is concluded that the balance among the pressures at the bottom of the cavity can be given by Eq. (5) for the FeOx-SiO_2 samples. It has been confirmed that the depth of cavity decreases with increasing the density of the sample.

Fig. 14. Schematic illustration of heat balance.

3.2.3. Relation between the Area of Convection Region and the Viscosity of Samples

It is considered that the area of the convection region can be determined by the heat balance. Figure 14 shows a schematic illustration of heat balance. In the centre of the sample, there is rapid convection in the direction from the centre to the borderline. The heat from the plasma arc is transported toward the borderline by convection into this region. Therefore, the heat transported to the borderline should increase with increasing the velocity of convection. As mentioned before, the aerodynamic drag force is the main driving force of the convection on the sample surface.

As known well as Newton's law of viscosity, the velocity gradient in fluid depends on its viscosity. Therefore, the velocity of convection (v_1) should decrease with an increase in the viscosity (η) of the sample under the constant aerodynamic drag force, which can result in a decrease in the heat (q_v) transported.

$$v_1 \propto 1/\eta \propto q_v \dots\dots\dots(10)$$

On the other hand, the velocity of convection near the edge of the sample was much slower than that in the centre. It is, therefore, considered that the heat is mostly transported by conduction near the edge of the sample. The heat (q_c) conducted to the edge can be expressed as²¹⁾

$$q_c = \frac{2\pi\lambda}{\ln(r_0/r_1)} (T_1 - T_0) \dots\dots\dots(11)$$

where λ is the thermal conductivity of the sample, r_0 and r_1 the radius of the sample and that of the convection region, respectively, T_0 and T_1 are the temperature at the edge of the sample and that at the borderline, respectively as shown in Fig. 13. At the steady state, q_v is equal to q_c :

$$q_v = q_c = \frac{2\pi\lambda}{\ln(r_0/r_1)} (T_1 - T_0) \dots\dots\dots(12)$$

Fig. 15. Relation between the region of the outward flow and the viscosity of the FeOx-SiO₂ sample at the arc current of 200 A and the arc length of 30 mm.

Argon gas flow rate	
○	$5.0 \times 10^{-5} \text{ Nm}^3/\text{s}$
□	$6.7 \times 10^{-5} \text{ Nm}^3/\text{s}$
△	$8.3 \times 10^{-5} \text{ Nm}^3/\text{s}$

From Eqs. (10) and (12), it is obvious that the r_1 should become smaller with increasing η , assuming that λ , T_0 and T_1 are constant. Figure 15 shows the relation between the radius of the convection region and the viscosity of the FeOx-SiO₂ samples. The viscosity of the FeOx-SiO₂ samples at 1673 K have been used for that of FeOx-SiO₂ system saturated with iron at Slag Atlas.²²⁾ It is found that the convection region becomes smaller as the viscosity increases. Thus, the area of the convection region is greatly influenced by the viscosity of the sample. It is also found that this radius becomes larger with an increase in the argon gas flow rate. Accordingly, it is concluded that the region of the convection is determined by heat balance between the heat transported by convection at the border and the heat transported by conduction at the edge.

5. Conclusions

The fusion behaviour of FeOx and FeOx-SiO₂ by argon plasma arc has been investigated. The experimental findings are summarised as follows:

- (1) The cavity formed under the plasma arc, and the pressures required to form the cavity are equal to the sum of the arc pressure and the argon gas pressure.
- (2) Convection occurred in the direction from the centre to the edge on the sample surface, and the main driving force of convection under the plasma arc is the aerodynamic drag force.
- (3) The temperature distribution is dependent on the argon gas flow rate and the dimension of the convection region. The heat from the plasma arc is mostly transported by convection on the sample.
- (4) The dimension of the convection region is dependent on the viscosity of the sample and determined by heat balance between the heat transported by convection at the border and the heat transported by conduction at the edge.

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