Low-temperature Synthesis of Aluminium Carbide

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(Received on November 17, 2010; accepted on March 22, 2011)

The Hall-Héroult process, the only commercial technology for aluminum production requires high energy and is a major origin of perfluorocarbons and greenhouse gases. A promising alternative process, carbothermal reduction of alumina to metallic aluminum has advantages of lower capital cost, less energy consumption, and lower emission of greenhouse gases. Carbothermal reduction processes under development are based on formation of aluminum carbide-alumina melts at high temperatures. Solid state carbothermal reduction of alumina is possible at reduced CO partial pressure. This paper presents results of experimental study of carbothermal reduction of alumina into aluminum carbide in argon, helium and hydrogen atmospheres at 1 500–1 700°C. The reduction rate of alumina increased with increasing temperature, and was significantly faster in helium and hydrogen than in argon. Increasing gas flow rate and pellet porosity, and decreasing pressure favour the reduction.

KEY WORDS: carbothermal reduction; alumina; aluminum carbide; solid state reduction.

1. Introduction

Aluminum is the most abundant metallic element, representing 8% of the earth’s crust. Metallic aluminum is the second most widely used metal next to steel. The Hall-Héroult process is essentially the only method for the commercial production of aluminum, which requires high energy consumption (~13 kWh/kg of aluminum), releases perfluorocarbons, and emits a large amount of greenhouse gases. High capital cost of electrolytic cells for producing aluminum is another drawback for this method.

Carbothermal reduction of alumina is the most promising alternative process to replace the current Hall-Héroult process for the production of aluminum, with high potential for greater productivity, lower capital investment, less consumption of electric power, and less emission of greenhouse gases. The major aluminum producers have researched this method over the last few decades. In one of the earliest works published in 1963, alumina was reduced in an electric arc furnace at 2 400–2 500°C with formation of a mixture of aluminum and aluminum carbide (Al₄C₃) with low content of alumina. Further development of carbothermal aluminum production evolved in the direction of a two-stage process. Cochran and Fitzgerald invented a stack-type reactor, which was separated into two zones. A liquid alumina–aluminum carbide mixture was produced in the upper reaction zone, and was transferred to the lower reaction zone, in which alumina reacted with Al₄C₃ with formation of liquid aluminum and carbon monoxide. The two-zone method was also used by Persson and Dougan and Southam.

Dmitriev and Karasev proposed to use an induction shaft furnace for carbothermal reduction of alumina to produce Al₄C₃, which was dissociated by electrolysis into aluminum and carbon in the lower zone of the same furnace. In Lacamera’s invention, alumina was carbothermally reduced into molten mixture of aluminum and Al₄C₃ (10–30 wt%) in an electric arc furnace at 2 000 to 2 100°C, and then aluminum scrap was added to cool the melt to 900 to 1 000°C to separate reduced aluminum. Unreacted Al₄C₃ was recycled to the high temperature electric arc furnace where it reacted with alumina to produce aluminum.

Since 2000, Alcoa and Elkem in collaboration with Carnegie Mellon University have carried out investigations on carbothermal production of aluminum using two-zone reduction vessel. Alumina was reduced in the first reaction compartment to form a 50% Al₂O₃–50% Al₄C₃ melt at approximately 2 000°C. Further reaction took place in the second compartment at approximately 2 200°C to form aluminum, which was tapped, degassed and cast.

Although extensive investigations have been made, no alternative process has been successful in replacement of the Hall-Héroult process. The major difficulties in development of a competitive carbothermal process include very high temperatures needed for reduction/smelting reactions, the formation of aluminum carbides, and many engineering problems in materials handling, including recovering of volatiles and delivery of energy to attain over 2 000°C. A lack of knowledge of reaction mechanisms and kinetics of alumina reduction is one of the main barriers to overcome these problems.

This work studies solid state reduction of alumina to Al₄C₃ under different conditions (gas atmosphere and temperature) with the aim to develop better understanding to solid state carbothermal reduction of alumina.

2. Experimental

The raw materials used in the study were alumina powder of 99.7% purity and <10 μm in size, and synthetic graphite with a powder size <20 μm. Both chemicals were supplied...
The reduction mixture was prepared by mixing raw materials with C/Al₂O₃ molar ratio of 6. A wet mixing method was used to obtain a uniform mixture. After drying, the powder was pressed statically into cylindrical pellets of 8 mm in diameter and about 10 mm in height.

The gases used in the study were argon, helium and hydrogen of 99.999% purity, all supplied by BOC Gases, Sydney, Australia. The flow rate of the gases was controlled by mass-flow controllers (model 5850E, Brooks Instrument, Hatfield, PA). The composition of effluent gas was monitored by a CO/CO₂/CH₄ IR analyzer (Advanced Optima AO2020, ABB, Germany).

The reduction experiments were carried out in a graphite furnace (Model 1000-3560-FP20, Thermal Technology Inc., USA). Figure 1 shows the schematic of the reaction system. A graphite tube of 10 mm i.d. and 19 mm o.d. was used as a sample holder and reactor, which was inserted into the external graphite tube of 24 mm i.d. to confine the gas from a furnace chamber. Both graphite tubes were coated with a thermo-settable resin, and heated up slowly, to form a layer of vitreous carbon so that the graphite tubes became gas impermeable. An alumina sheath was inserted from the bottom which worked as an aluminum vapor condenser/deposit collector. The reduction temperature was controlled by a type B thermocouple inserted from the side of the furnace. After the sample was loaded into the reactor, the furnace with established temperature profile was first vacuumed to <0.4 torr residual pressure, and then was heated to ~400°C to further remove the gases and water adsorbed inside the graphite furnace. After the vacuum reached <0.4 torr, the furnace was refilled with Ar gas, and the reactor was purged by the gas used in the experiments until readings of CO, CO₂ and CH₄ contents from the gas analyzer approached zero. Then the furnace was heated at 60°C/min to the experimental temperature, and the readings from the gas analyzer started to be recorded. After reduction completed, the sample was cooled within the furnace with continuously flowing gas until the temperature was less than 871
100°C. Samples and deposits were collected and stored in desiccators to avoid reacting of Al₄C₃ with moisture.

Phase composition of the reduced samples was analyzed with the powder X-Ray diffraction (Philips X’pert Multipurpose X-Ray Diffraction System). The oxygen content of the samples was measured by LECO (Model TC-436DR). The extent of reduction was defined as percentage of oxygen removed from alumina.

3. Results

3.1. Effects of Temperature and Gas Atmosphere

Carbothermal reduction of alumina in isothermal experiments was studied in hydrogen, helium and argon in a temperature range of 1 500 to 1 700°C. All experiments were carried out for 300 min under atmospheric pressure with a gas flow rate of 1 NL/min. The extent of alumina reduction versus temperature is shown in Fig. 2. Both temperature and gas atmosphere had strong effects on the reduction. The reduction was the slowest in argon. At 1 500°C, the extent of reduction in argon was only 5%, and Al₄C₃ was undetectable by the XRD analysis. The extent of reduction increased to 10% and 43% when the temperature was increased to 1 550 and 1 600°C, respectively. At 1 700°C, the extent of reduction was 97%. The extent of reduction in hydrogen and helium was about the same; the difference at 1 500–1 550°C was within the error of measurement of oxygen content by LECO analysis, which was relatively high because of high residual oxygen content in the reduced samples when the extent of reduction was low.

Figure 3 compares the CO evolution at 1 600°C in different gases for 120 min. This figure demonstrates that the reduction of alumina was the slowest in argon, while the rates of reduction in helium and hydrogen were practically the same.

Alumina reduction in hydrogen and helium at 1 600°C and 1 700°C is compared in Figs. 4(a) and 4(b) respectively. At these relatively high temperatures, reduction curves obtained in hydrogen and helium were similar. At 1 600°C (Fig. 4(a)), the reduction reached about 20% within the first 30 min and 45% within 60 min. After 180 min of reduction, more than 90% of reduction had achieved. The reduction was close to completion after 300 min of reduction. At 1 700°C (Fig. 4(b)), up to 50% of reduction had achieved within the first 30 min. This was increased to 90–95% after 60 min reduction. The reduction was close to completion in 120 min.

3.2. Effect of Gas Pressure and Flow Rate

The effect of pressure on the carbothermal reduction was investigated in hydrogen and helium by changing the gas pressure from 100 kPa (atmospheric pressure) to 140 kPa at 1 600°C and gas flow rate 1.0 NL/min. The reduction period was 120 min. The experimental results are presented in Table 1. In both gas atmospheres, the extent of reduction decreased with increasing pressure. In hydrogen, the extent of reduction decreased by 16% and in helium by 19% when the gas pressure was increased from 100 to 140 kPa.

The effect of gas flow rate on the reduction of alumina was studied in hydrogen, helium and argon at 1 600°C (Fig. 5). The reduction was carried out in (a) argon, (b) helium and (c) hydrogen.
was investigated in Ar, He and H₂ at 1 600°C, atmospheric pressure, and 120 min reduction time. The flow rate varied from 1 NL/min to 0.5 NL/min. Table 2 shows the extent of reduction of different experiments. It can be seen that decreasing the gas flow rate decreased the extent of reduction of alumina consistently.

3.3. Effect of Pellet Porosity
The influence of pellet porosity on alumina reduction was studied at 1 600°C in hydrogen, helium and argon. The pellet porosity was varied by the addition of naphthalene from 0–30 vol%, while pellet size was constant. The total gas flow rate in all experiments was maintained at 1 NL/min. The reduction curves obtained in experiments in argon, helium and hydrogen are presented in Fig. 5. Increasing pellet porosity had a positive effect on the carbothermal reduction of alumina which was particularly strong in argon.

3.4. Phase Development in the Progress of Alumina Reduction in Helium and Hydrogen
XRD patterns of samples taken in progress of reduction at 1 600°C in hydrogen and helium are shown in Figs. 6 and 7, correspondingly. Phase development in the progress of reduction in hydrogen and helium at 1 600°C was similar. Al₄C₃ peaks were detected after 30 min reduction. The Al₂O₃ peaks decreased and the relative intensity of Al₄C₃ peaks increased with increasing the reduction time. After 300 min, no Al₂O₃ peaks were detected.

Figure 8 presents the XRD patterns of samples in the progress of reduction in hydrogen at 1 700°C. After 30 min reduction, significant amount of Al₄C₃ was formed. At 60 min, the Al₂O₃ peaks were very weak, while peaks of Al₄C₃

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Fig. 6. XRD patterns of samples reduced in hydrogen at 1 600°C for different time. The pressure was 100 kPa and gas flow rate was 1.0 NL/min.

Fig. 7. XRD patterns of samples reduced in helium at 1 600°C for different time. The pressure was 100 kPa and gas flow rate was 1.0 NL/min.

Fig. 8. XRD patterns of samples reduced in hydrogen at 1 700°C for different time. The pressure was 100 kPa and gas flow rate was 1.0 NL/min.
phase became strong. The reduction was close to completion at this stage. From 120 min and longer reduction time, Al$_2$O$_3$ peaks were undetectable. During this period, the heights of Al$_4$C$_3$ peaks relative to the graphite peak became remarkably lower, showing that the carbide content decreased with extension of reduction. This demonstrates that Al$_4$C$_3$ was not stable at this temperature; decomposition of Al$_4$C$_3$ was significant at 1 700°C.

The XRD patterns of the samples reduced in helium at 1 700°C for different time are presented in Fig. 9. Overall, the phase development in helium was close to that in hydrogen under otherwise the same conditions. After reduction for 60 min, residual alumina in the reduced sample was clearly seen, however, it disappeared after 90 min. It follows from Fig. 9, that decomposition of Al$_4$C$_3$ occurred at 1 700°C, however, it was slower than in hydrogen.

4. Discussion

The overall reaction of conversion of alumina to aluminium carbide Al$_4$C$_3$ is:

\[ 2\text{Al}_2\text{O}_3 + 9\text{C} = \text{Al}_4\text{C}_3 + 6\text{CO}; \]
\[ \Delta G^0 = 2398 - 1.06T \quad (kJ) \]

The Gibbs free energy of Reaction (1) and later reactions were obtained from Ref.\textsuperscript{16} The partial pressure of CO for this reaction in equilibrium with solid alumina and aluminium carbide is shown in Fig. 10; it increases with increasing temperature. At 1 400°C, the equilibrium CO partial pressure is only 0.05 kPa. It increases to 1.13 kPa at 1 600°C and approaches atmospheric pressure at 2 000°C. Therefore, reduction of alumina at temperatures below 2 000°C is thermodynamically possible only at reduced CO partial pressure. Increasing temperature favours the reduction of alumina both kinetically and thermodynamically. Increasing gas flow rate and decreasing pressure of the gas result in decrease in CO partial pressure in the gas phase, and facilitate carbothermal reduction of alumina.

It is broadly accepted that carbothermal reduction of solid oxides proceeds through the gas phase, when an oxide is reduced by CO which is regenerated by the Boudouard reaction.\textsuperscript{17–20} The reduction of alumina by CO can be presented by the following reaction:

\[ 2\text{Al}_2\text{O}_3 + 12\text{CO} = \text{Al}_4\text{C}_3 + 9\text{CO}_2; \]
\[ \Delta G^0 = 930.2 + 0.466T \quad (kJ) \]

Apart from this reaction, alumina can be reduced by carbon to aluminum or Al$_2$O vapor following Reactions (3) and (4):

\[ \text{Al}_2\text{O}_3 + 3\text{C} = 2\text{Al}(g) + 3\text{CO}; \]
\[ \Delta G^0 = 1948 - 0.800T \quad (kJ) \]

\[ \text{Al}_2\text{O}_3 + 2\text{C} = \text{Al}_2\text{O}(g) + 2\text{CO}; \]
\[ \Delta G^0 = 1261 - 0.536T \quad (kJ) \]

Reduction of alumina in these reactions can also proceed by CO as a reductant. Al in the gas phase further reacts with Al$_2$O$_3$ to form Al$_2$O vapor:

\[ \text{Al}_2\text{O}_3 + 4\text{Al}(g) = 3\text{Al}_2\text{O}(g); \]
\[ \Delta G^0 = -113.1 - 0.0084T \quad (kJ) \]

Depositing on the graphite particles, Al$_2$O can be converted to Al vapour (Reaction (6)) and aluminium carbide (Reaction (7)):
\[
\begin{align*}
\text{Al}_2\text{O}_3(g) + C &= 2\text{Al}(g) + \text{CO}; \\
\Delta G^\circ &= 687 - 0.264T \quad (\text{kJ}) \\
&\vdots \\
2\text{Al}_2\text{O}_3(g) + 5\text{C} &= 2\text{Al}_4\text{C}_3 + 2\text{CO}; \\
\Delta G^\circ &= -124 + 0.016T \quad (\text{kJ})
\end{align*}
\]

Equilibrium partial pressures of CO₂ (Reaction (2)), Al (Reaction (3)) and Al₂O (Reaction (4)) are presented in Fig. 10.

The equilibrium partial pressure of CO₂ is by 4–7 orders lower than those of Al and Al₂O. Diffusion of CO₂ from alumina particles to graphite particles is very slow, and can be a rate limiting stage for the Boudouard reaction. It can be suggested that gaseous Al and Al₂O play a major role in the reduction of alumina to aluminum carbide.

Reduction of alumina to gaseous Al and Al₂O was observed in experiments at high temperatures: the alumina plug at the bottom of the reactor was strongly corroded, and almost disappeared in some cases; the evaporated volatiles were deposited on the low temperature section of the reactor tube. The deposit was identified by XRD to be mainly Al₂O₃C, which was formed by reaction of Al and Al₂O vapours with CO as follows:

\[
\begin{align*}
2\text{Al}_2\text{O} + 2\text{CO} &\rightarrow \text{Al}_2\text{O}_3\text{C} + \text{C} \quad \vdots \\
4\text{Al} + 4\text{CO} &\rightarrow 4\text{Al}_2\text{O}_3\text{C} + 3\text{C} \quad \vdots
\end{align*}
\]

Recovery of aluminium from Al₂O and Al vapours is an important part in implementation of the carbothermic process. Fruehan et al. studied reactions of gaseous Al₂O and Al with metallurgical and petroleum coke and wood charcoal. They observed that reaction products depended on the temperature and type of carbonaceous material. In reaction with wood charcoal and to less extent with petroleum coke, aluminium carbide or Al₂O₃–Al₄C₃ slag were formed. Carbide Al₄C₃ was formed at 1 940–1 960°C, temperature interval for the slag formation was 1 910–1 940°C. Our work shows that aluminium carbide can be formed at a much lower temperature.

Fruehan et al. concluded that partial pressures of Al₂O and Al are the major uncertainty in carbothermal reduction of alumina. They estimated partial pressures of Al₂O and Al in the gas phase in equilibrium with Al₂O₃–Al₄C₃ melt saturated with Al₄C₃ at 1 950–2 020°C from measurement of the weight loss and CO partial pressure. Their results are given in Table 3. CO partial pressure in experiments in work refers to 50–55 kPa. These experiments were conducted in flowing argon (0.5 L/min) with (Al₂O₃–Al₄C₃) slag saturated with Al₄C₃ in a graphite crucible.

It can be noted that effect of temperature in the range 1 980–2 020°C on Al₂O partial pressure in experiments was insignificant; experimental data were scattered between 9 kPa and 12 kPa.

CO partial pressure in equilibrium with pure solid alumina and aluminum carbide (Reaction (1)) is equal to 100 kPa at 1 989°C. The effect of CO partial pressure on Al₂O and Al partial pressures can be illustrated by calculation of P_{Al2O} and P_{Al} in equilibrium with solid alumina with CO partial pressure equal to 55 kPa and 100 kPa (Reactions (3) and (4)), which are also given in Table 3. Decreasing CO partial pressure significantly increases partial pressures of Al₂O and Al vapours.

As mentioned above, partial pressures of Al₂O and Al are significantly higher than P_{CO2} (Fig. 10). This gives a ground to suggest that Al₂O and Al gases were involved in reduction of alumina to aluminium carbide as described by Reactions (5)–(7). The following mechanism can be suggested for the reduction of alumina. The reduction starts with reduction of alumina by carbon to Al vapour (Reaction (3)) and Al₂O vapour (Reaction (4)); alumina is further reduced to Al₂O vapour by gaseous Al (Reaction (5)), while Al₂O is reduced to Al vapour by reacting with graphite (Reaction (6)). Above mechanism is graphically presented in Fig. 11. It was concluded in work that the rate of reaction of Al₂O vapour with carbon was controlled by mass transfer of Al₂O through aluminium carbide which was formed on the coke (char) surface.

Results of this work showed that reduction of alumina in helium and hydrogen was much faster than in argon. The difference of reaction rates in these gases reflects the effect of diffusion of gaseous species on the reduction rate, what supports the suggested reduction mechanism. Internal mass transfer in the gas phase plays a major role in the reduction kinetics in the reaction cycle: Al vapour reacts with Al₂O₃ to

\[
\text{Al}_2\text{O}_3(g) \rightarrow \text{Al}_2\text{O}_3(g) + (\text{CO})
\]

\[
\text{Al}_4\text{C}_3 + (\text{CO}) \rightarrow 4\text{Al}_2\text{O}_3(g) + \text{C}
\]

![Fig. 11. Graphical presentation of the reaction mechanism of carbothermal reduction of alumina.](image)

Table 3. Partial pressures of Al and Al₂O measured in 13) and calculated for Reactions (3) and (4) in equilibrium with solid alumina.

<table>
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</thead>
<tbody>
<tr>
<td>Al₂O partial pressure, kPa (from)</td>
<td>5.6</td>
<td>4.0–4.5</td>
<td>9.0</td>
<td>12.2</td>
<td>11.0</td>
</tr>
<tr>
<td>Al₂O partial pressure, kPa, calculated for Reaction (4) for P_{CO} = 55 kPa and P_{CO} = 100 kPa (in brackets)</td>
<td>8.13</td>
<td>12.8</td>
<td>20.2</td>
<td>36.4</td>
<td>65.2</td>
</tr>
<tr>
<td>Al partial pressure, kPa, calculated for Reaction (3) for P_{CO} = 55 kPa and P_{CO} = 100 kPa (in brackets)</td>
<td>2.56</td>
<td>3.65</td>
<td>5.17</td>
<td>8.16</td>
<td>12.8</td>
</tr>
</tbody>
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form gaseous Al$_2$O; the latter diffuses to graphite and reacts with carbon regenerating Al vapor; then the Al vapor diffuses to Al$_2$O$_3$ phase. The partial pressures of Al and Al$_2$O are relatively low. The equilibrium partial pressure of Al$_2$O at 1 600°C and 1 700°C is 5.96×10$^{-2}$ kPa and 2.55×10$^{-1}$ kPa, correspondingly. Equilibrium pressure of Al vapour at these temperatures is close to that of Al$_2$O (Fig. 10). The driving force for diffusion of Al vapour from graphite to alumina and of Al$_2$O from alumina to graphite (the difference in Al and Al$_2$O partial pressures at the alumina-gas and graphite-gas interfaces) is also low. This makes the overall reaction rate sensitive to the diffusivity of gas species. The diffusion coefficients of Al, Al$_2$O, CO and CO$_2$ in hydrogen, helium and argon estimated following Fuller et al.$^{21}$ are listed in Table 4. The atomic and structural diffusion volume increases of Al is not available in literature. For comparing the diffusion coefficients of Al and Al$_2$O species in different gases, it was assumed to be the same as that of Ar. The diffusion coefficients of gas species are close in hydrogen and helium, and are much higher than in argon (by a factor of 10–20 at 1 600°C). This explains why the reduction of alumina in hydrogen proceeds with about the same rate as in helium.

It has been well established that carbothermal reduction of manganese and titanium oxides is much faster in hydrogen than in helium and argon.$^{15,20,22-26}$ The enhancing effect of hydrogen on the carbothermal reduction was attributed to the formation of methane which plays a role of carbon carrier. However, the rate of carbothermal reduction of alumina in hydrogen is close to that in the helium atmosphere. This explains why the role of methane in reduction of alumina is limited.

Partial pressure of methane formed by reaction of hydrogen with carbon is equal to the partial pressure of Al$_2$O at 1 527°C and to the partial pressure of Al at 1 600°C. At 1 600°C and above, $P_{CH_4}$ is lower than partial pressures of both, Al$_2$O and Al (Fig. 10). At 1 700°C, the difference between partial pressures of CH$_4$ and Al$_2$O is more than one order in magnitude; this makes Al$_2$O and Al preferential gaseous species in the alumina reduction.

As shown in Figs. 8 and 9, Al$_4$C$_3$ in H$_2$ atmosphere is less stable than in helium. Correspondingly, more deposit was collected in reduction experiments in hydrogen than in helium and argon.

Increasing gas flow rate increased the overall CO partial pressure in the bulk gas and inside the pellet, which benefitted Reactions (6), (7) and overall Reaction (1) and so had a positive effect on the reaction rate. The effect of gas flow rate was particularly significant in argon at flow rates below 1 L/min. Diffusion coefficient of CO in argon is much lower than in hydrogen and helium, what makes its internal diffusion from the pellet to the bulk gas slower, resulting in higher difference between the partial pressures of CO in the pellet’s interior and outside the pellet, or internal diffusion control. This explains why increasing gas flow rate had a stronger effect on reduction of alumina in argon than in hydrogen or oxygen.

Effect of gas pressure on alumina reduction was studied only in hydrogen and helium. In both cases, decreasing the gas pressure increased the reduction rate. This effect can also be attributed to the decrease in CO partial pressure. In addition, it also increased the mass transfer of gaseous species as diffusion coefficients of gases increase with decreasing pressure.

Increasing the pellet porosity increased the reduction rate in all three gases. Increased porosity increased the reaction interfacial area and the internal diffusion rate, both with a positive effect on the reaction rate. The effect of pellet’s porosity on alumina reduction was much stronger in argon than in hydrogen and helium, which means that diffusion is an important factor affecting the reduction kinetics.

Table 4. Estimated diffusion coefficients (cm$^2$/s) of Al$_{16g}$, Al$_{16a}$, CO and CO$_2$ in hydrogen, helium and argon at 1600°C.

<table>
<thead>
<tr>
<th>Gas species</th>
<th>H$_2$</th>
<th>He</th>
<th>Ar</th>
</tr>
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<tbody>
<tr>
<td>Al</td>
<td>10.8</td>
<td>13.3</td>
<td>0.92</td>
</tr>
<tr>
<td>Al$_2$O</td>
<td>7.2</td>
<td>8.6</td>
<td>0.42</td>
</tr>
<tr>
<td>CO</td>
<td>10.3</td>
<td>12.7</td>
<td>0.87</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>8.6</td>
<td>10.4</td>
<td>0.60</td>
</tr>
</tbody>
</table>

5. Conclusions

Carbothermal reduction of alumina was studied in hydrogen, helium and argon in the temperature range of 1 500–1 700°C. Alumina was reduced to aluminium carbide Al$_4$C$_3$. Carbothermal reduction of alumina involves Al and Al$_2$O vapor, which play a major role in the reduction mechanism.

The reduction rate increased with increasing temperature. The formation of aluminium carbide in hydrogen and helium was close to completion in 180 min at 1 600°C and 60 min at 1 700°C. In argon, higher temperature and longer reaction time were needed. Difference in the reduction behaviour in hydrogen/helium and in argon was attributed to difference in the diffusion coefficients of gaseous Al, Al$_2$O and CO, which are much higher in H$_2$/He than in Ar.

Increasing gas flow rate or decreasing gas pressure increased the reduction rate what was attributed to reduced CO partial pressure.

Increasing the pellet porosity increased the reduction rate in all three gas atmospheres, what was explained by increasing the reaction surface area of the pellet and internal diffusion of CO into the bulk gas.

Acknowledgements

This research was supported under Australian Research Council Discovery Projects funding scheme (project number DP0663998). Professor Ostrovski is the recipient of an Australian Research Council Professorial Fellowship (project number DP0771059).

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