

Reduction of taconite concentrates in a cyclone reactor

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Abstract — A cyclone reactor system for the partial reduction and melting of taconite concentrate fines was designed and operated. A nontransferred arc plasma torch was employed as a heat source. Taconite fines, carbon monoxide and carbon dioxide were fed axially into the reactor, while the plasma gas was introduced tangentially into the cyclone. The average reactor temperature was maintained above 1673°K (1400°C), and reduction experiments were performed under various conditions.

The influence of the following parameters on the reduction of taconite was investigated: carbon monoxide to carbon dioxide inlet feed ratio, carbon monoxide inlet partial pressure and average reactor temperature. The interaction of the graphite lining with carbon dioxide and taconite were also studied.

Introduction

Cyclone reactors were used in boiler construction during the 1940s (Melecheri, 1976). The appeal of the cyclone configuration is that it increases the efficiency of the flash-combustion process through turbulence induced increases in mass transfer, heat exchange and combustion rates. Pyrometallurgical processing utilizing cyclone reactors was first suggested in the mid-1950s, when the process was first used in a Sardina plant to treat antimony sulfide concentrates (Tian-cong, 1988). Due to severe wear and other difficulties, the plant is no longer in operation.

At about the same time, investigators in the USSR began using cyclone reactors to smelt copper ores and concentrates. This led to the development of the well-known KIVCET process (Melecheri, 1976). The Flame Cyclone Reactor (FCR) (Ruehl, 1986, Bernde, 1985) and the CONTOP (Gamruth, 1985) processes are two additional technical developments in copper metallurgy in which a smelting cyclone is utilized as a reaction chamber.

In spite of the success reported in employing cyclones as reaction chambers in the processing of sulfidic ores and concentrates, little attention has been paid to their use in the pyrometallurgical treatment of iron ores. The earliest attempt was conducted by Johnson and Davidson in 1955 (1964), when the feasibility of producing metallic iron from a prerduced iron ore in a vertical cyclone furnace was investigated. Because of technical difficulties and wear of the lining, the research was terminated in 1964. Recently, the US Bureau of Mines developed a high-temperature rocket combustion reactor for iron ore reduction (Kazonich, 1993).

Range in Minnesota (Peterson, 1983, 1981a, 1981b, Pahlman 1979). Development of an economic and applicable technology to process these reserves would ensure an adequate supply of iron for the domestic iron and steel industry and would decrease significantly the growing dependence on foreign suppliers.

Cyclone smelting of fine taconite concentrate has advantages because of the following:

- a higher throughput in a small reactor;
- enhanced heat and mass transfer rates, due to increased mixing caused by the high turbulence within the cyclone chamber (Barin, 1983);
- higher temperatures can be achieved, resulting in reactions approaching completion in a relatively short time;
- the separation of the liquid and gaseous products is accomplished within the cyclone chamber;
- agglomeration of the ore concentrate is not needed, reducing the operating costs significantly.

To make the process more economically attractive, the use of sub-bituminous coal, oxygen and the cogeneration of electricity might be required. In addition, to effect the reduction reactions, the carbon monoxide to carbon dioxide ratio needs to be maintained at high levels within the reactor system. Another drawback of the process may be that only partial reduction and melting of the ore is possible, which would require subsequent bath smelting.

The use of a cyclone for melting and partial reduction of fine taconite concentrates in conjunction with bath smelting (using bath producer gas) was first suggested by Bartlett (1988). The proposed process is composed of two steps: partial reduction and melting of the solid charge in a cyclone furnace and bath smelting as a final reduction step. The gases that exit the bath, being rich in carbon monoxide, are partially recycled to the cyclone reactor where reduction to liquid wustite is accomplished. Excess gas is burned in air to produce steam for power generation.

This research project is concerned with the prerduction and melting of taconite in a cyclone reactor.

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Experimental system

The experimental system used in this study is shown in Fig. 1. The cyclone was fabricated from a 0.36-m (14") ID, 0.41-m (16") OD, 0.61-m (24") long steel shell and from a 0.006-m (1/4") cooling jacket with two 0.15-m (6") diam. tangential inlets. The inlets on the cooling jacket are located 180° apart and centered ≈0.13 m (5") from the top. One inlet is used as the burner port and the other is used as the plasma torch port. The cyclone has a circular steel lid with a 0.025-m (1") inlet port that allows axial injection of the taconite feed. The steel cover and the tangential ports both have 0.006-m (1/4") cooling jackets.

The conical section is 0.15 m (6") high with an exit diameter of 0.15 m (6"). After applying a layer of high-temperature sealant around the periphery of each section, the cyclone is assembled gas-tight with bolts

Graphite (grade 6222-P from Graphite products) is used as a lining. The graphite (0.23 m (9") ID, 0.25 m (10") OD and 0.61 m (24") long) has the same general construction as that of the steel shell. The conical section is also lined with graphite and is insulated with graphite felt. This exit lining has a diameter of 0.05 m (2") and extends 0.05 m (2") inside the collection chamber.

The cyclone reactor is placed on top of a 0.3-m (12") high, 0.3-m (12") wide, 0.6-m (24") long, rectangular collection chamber. All six faces of the chamber are water cooled (1/4" cooling jacket) through separate lines. Also, a cooling coil (made of 0.012 m (1/2") copper tubing) is installed at the discharge end of the chamber. A fire-clay crucible inside the chamber is used to collect the molten product. The crucible is 0.15 m (6") high and 0.10 m (4") in diameter. Gases leaving the chamber enter a cylindrical filter to trap and collect the entrained particles. The filter is made from a 0.20-m (8") ID, 0.30-m (12") long tubular-steel shell containing a filter bag made of 0.5- μ m Nomex cloth with a twelve-sided star-shaped folded periphery. The filter is water cooled using a cooling coil to ensure a temperature of less than 423°K (150°C). A pressure gauge is installed at the filter inlet to monitor the incoming gas pressure.

Gases exiting the filter pass through a burner that converts the carbon monoxide to carbon dioxide, thus minimizing the hazardous potential of the gases. The combustion gases are vented to a stack.

A nontransferred arc plasma torch (Model PT50C612, acquired from Plasma Energy Corporation) is used to provide the required energy. A mixture of argon and nitrogen is used as the plasma gas. The flow rates of both gases are measured and recorded separately. The torch is attached to a 96 KW power supply (Halmar).

Reactants are fed axially into the cyclone through a 0.010-m (3/8") copper pipe connected to a graphite tube through a pipe union. A Metco powder feeder (Model 3MP) is used to feed the taconite powder using a carbon dioxide-argon mixture as a carrier gas. Carbon monoxide is introduced through a tee at the end of the copper tube carrying the taconite feed. Flow rates of the three gases are measured and recorded separately.

The system includes three ports along the cyclone reactor

Table 1 — Chemical composition of taconite concentrates as provided by LTV Steel.

Component	Percentage
Iron	67.04
Silica	4.50
Phosphorous	0.20
Wustite	21.01
Magnetite*	67.70
Hematite*	25.81
* Calculated	

3300). The third line is attached to an IR gas analyzer (Siemens, Model Ultramat-22P) that is used to monitor and record the carbon monoxide and carbon dioxide composition at the discharge end of the reactor.

Temperatures are measured and recorded using type "C" thermocouples located at three points along the cyclone. All sections of the cyclone and collection chamber have separate cooling lines, and all water lines have flow meters and type "K" thermocouples.

The information obtained from the system is interfaced with a data acquisition system. The system consists of an IBM PC (Model 30) and Metrabyte analog and digital boards. The conversion boards are connected to the thermocouples, flow sensors, pressure transducers and power-supply meters. Data from each experimental test are recorded and stored separately.

Experimental procedures

Fine taconite concentrates and carbon monoxide-carbon dioxide gas mixtures are the primary reactants in this research. The taconite powder contains various particle sizes but mainly consists of particles in the 5 to 45 μ m range. The chemical composition of the concentrate is reported in Table 1. Table 1 shows that the ore consists mainly of magnetite (67.70% Fe₃O₄, 25.81% Fe₂O₃) with ≈7% impurities. The taconite concentrate was obtained from LTV Steel Mining Company.

Technical-grade carbon monoxide is used as a reductant. Carbon dioxide is fed to the powder feeder and acts as a carrier gas (after being mixed with argon). The reactants are injected axially at the top of the cyclone, just above the point of plasma gas injection. Flow rates of carbon monoxide, carbon dioxide and taconite are adjusted to maintain a predetermined CO/CO₂ ratio at the cyclone discharge. The argon flow rate is adjusted to maintain a fixed flow rate of the carrier gas. The gas flow rates are measured and recorded using mass flow meters. Delivery pressures of these gases are fixed at 345 kPa (50 psi). The taconite concentrate is oven dried for eight to ten hours at 383-393°K (110-120°C). Drying prevents clogging of the powder feeder and maintains a more uniform flow of the concentrate into the reactor. Very little weight change was observed during drying. The taconite feed rate is fixed at 40 g/min.

The plasma torch is operated using an argon-nitrogen mixture as the plasma gas. The flow rate of argon ranges from 0.06-0.07 m³/min (2.2-2.5 scfm) and that of nitrogen is 0.02-0.03 m³/min (0.8-1.0 scfm). Detailed description of the plasma system and its operating parameters are published elsewhere (Abdel-latif, 1991).

While the system is being heated to the desired temperature, argon (as part of the carrier gas) is continuously fed into the cyclone to maintain a positive pressure at the top of the reactor. As the temperature at the cyclone discharge wall reaches 1623°K (1350°C), the carrier gas flow rate is increased to the desired value (usually 0.017 m³/min (0.6 SCFM)). The carbon dioxide flow rate is controlled so that the CO/CO₂ partial pressure ratio is fixed at the cyclone exit (as theoretically calculated). After the cyclone temperature

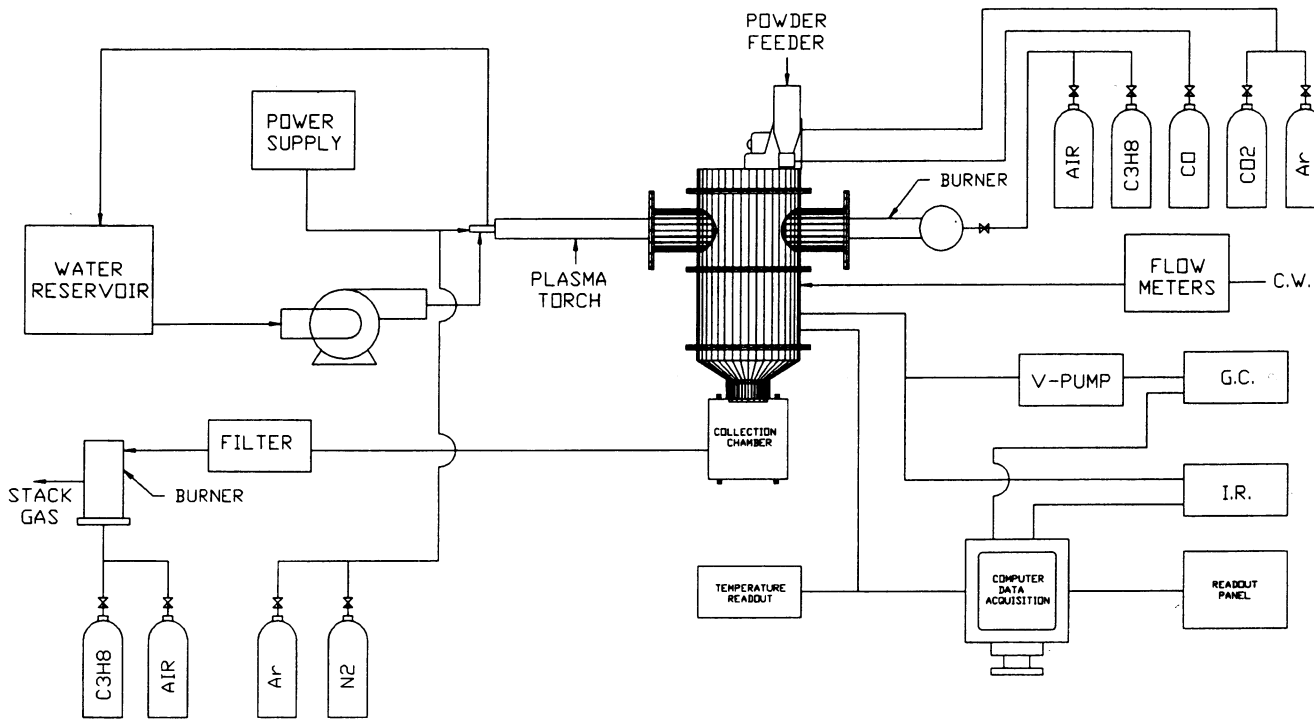


Fig. 1 — Schematic representation of the experimental system.

Taconite is fed for about 20 min. in most experiments. After taconite injection has begun, the cyclone temperature drops by 25-30°K before reaching a new steady-state temperature. As this time is reached, gas samples are withdrawn and analyzed using the gas chromatograph. Meanwhile, the IR gas analyzer is monitored continuously, and carbon dioxide and carbon monoxide analyses are recorded for the gas exiting the cyclone.

When the taconite and reacting gas feeding is stopped, the plasma torch is kept operating for 10 min. to prevent solidification of molten material inside the reactor and to give the melt additional time to flow out of the reactor into the crucible. After the plasma torch is shut off, the argon flow continues into the cyclone to prevent reoxidation of the product formed by any infiltrating air during the cyclone cooling.

Experimental results

The material collected in the crucible, filter bag and cyclone discharge was removed, weighed and saved for later analysis. Typically, 3.5% to 10.0% of the product was collected in the filter bag and 10% to 27% was collected in the crucible. The remainder remained in the reactor, mostly at the wall of the cyclone discharge.

The filter product consisted of very-fine powder that was apparently swept away with the gas phase and trapped in the filter bag. The crucible contained the following three types of material: fine-powder that settled out upon expansion and rapid cooling of the gas as it entered the collection chamber; material having a plate-like structure with loosely-held frozen particles; and a condensed, spherically-shaped solid mass. The cyclone product had a plate-like structure in the form of an ingot. The plates were relatively tightly bonded.

Upon dismantling the reactor lid at the conclusion of each

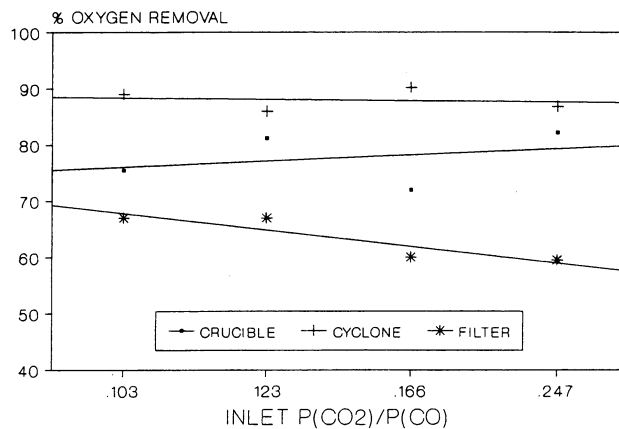


Fig. 2 — Oxygen removal vs. inlet $P(\text{CO}_2)/P(\text{CO})$.

addition, there were numerous spherically-shaped particles that were frozen onto the walls. The size of these spheres appeared to be random and ranged from <0.1 cm to >1 cm diameter. Chemical analysis of this material was always consistent and showed more than 95% iron.

Carbon dioxide/carbon monoxide feed ratio

In this set of experiments, the taconite feed rate was fixed at about 40 g/min, the carbon monoxide flow rate was 0.017 m³/min (0.6 scfm) and the input energy was 39 to 41 KW. The average reactor temperature was maintained at 1783° (1510°C). The carbon dioxide flow rate was varied between 0.0017 to 0.0042 m/min (0.06-0.148 scfm) to give an inlet CO_2/CO ratio of 0.100 to 0.247. Figure 2 presents the percentage of oxygen removal from the feed material, based on the material balance calculations (Abdel-latif, 1991). Figure 2 clearly indicates that the inlet CO_2/CO parti-

considering one product fraction at a time. On the average, the cyclone product analyzed 89.82% iron. This compares to 86.67% for the crucible material and 82.54% for the filter samples.

The filter bag samples showed lower oxygen removal. This is partly because the fines collected in the filter bag appeared to have been suspended in the gas phase and exited the reactor before there was sufficient time for more complete reduction. The three flow zones in a smelting cyclone, described by Taylor and co-workers (1991a, 1991b) and by Hou (1991), might have contributed to the lower degree of conversion of this portion of the product. Towards the cyclone center, there is a low-pressure zone where the gas and suspended particles short-circuit and flow out of the reactor with no significant tangential velocity. When this occurs, particles flowing in this zone travel at essentially the same speed as that of the gas phase. The result would be a much shorter reaction time and the lowest conversion. The reduction reactions in this zone are between the carbon monoxide present in the gas phase and the suspended solid particles (gas-solid reactions).

In contrast, the cyclone product exhibits the highest oxygen removal. This could be attributed to several factors. First, the carbon monoxide to carbon dioxide ratio was consistently very high within the cyclone, ensuring that the reduction of iron oxides could go to completion (provided the reaction time is sufficiently long). The high $P(\text{CO})/P(\text{CO}_2)$ ratio was due to the reaction between the carbon dioxide and the graphite lining at the elevated smelting temperatures employed. Second, this fraction formed a molten film that covered the lower portion of the lining. The liquid film would then react with the solid carbon as well as with carbon monoxide in the gas phase. Carbon dioxide can react with the carbon to regenerate carbon monoxide through the gasification reaction. The net results of these reactions would be higher oxygen removal and lower CO_2/CO ratios.

The liquid film that formed on the walls resulted from that portion of the feed that was immediately thrown onto the walls (either as solid particles, molten droplets or both). Once the film develops, it flows downward by gravitational forces, and, due to its high viscosity, it travels at a very-low speed relative to the gas, providing additional time for it to react with the carbon monoxide and the lining. At the cyclone discharge walls, the temperature drops below the melting point of the material, leading to its solidification. Once solidified, the material continues to react with the carbon monoxide as the gas flows past it. The material was typically nonporous and fairly homogeneous in composition. The overall effect of these factors would be the higher degree of reduction observed.

Some of the melt would flow into the crucible and collect there before it solidified on the discharge walls. In addition, molten droplets entrained in the gas phase, particularly in the high-flow zone (Taylor, 1991a), may discharge into the crucible before being carried to the lining walls. These droplets would have less reaction time than the molten film. Also, in the high-velocity zone, the main reactions are between these molten droplets and the carbon monoxide. When taking these factors together, one would expect lower reduction and less oxygen removal for the crucible material, compared to the cyclone product.

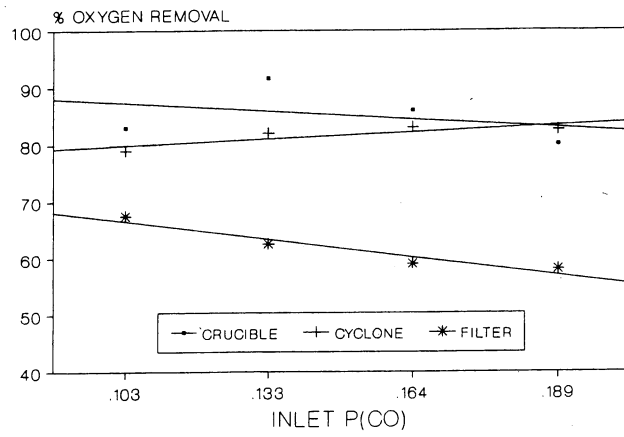


Fig. 3 — Oxygen removal vs. inlet P(CO).

reactor. The taconite flow rate was fixed at approximately 40 g/min and the input energy was in the range of 39-40 KW, resulting in an average cyclone temperature very similar to that of the previous set. The carbon monoxide flow rate was varied between 0.089-0.0236 m^3/min (0.313-0.833 scfm), giving an inlet CO partial pressure of 11,145-19,250 Pa (0.11-0.19 atm) (assuming the system's total pressure is 101,350 Pa (1.0 atm)). This assumption is based on the observation that no pressure increase was detectable with the pressure gauge installed at the discharge end of the collection chamber.

The percentage of oxygen removal is presented in Fig. 3. Clearly, these results suggest that the degree of reduction is not significantly affected by the initial partial pressure of carbon monoxide. Also, there appears to be no difference between the crucible and the cyclone materials (given the absolute experimental error of 3% in the procedure employed in determining the total iron in a given sample). The filter samples exhibit a lower degree of reduction for the reasons stated earlier.

In comparing Fig. 2 with Fig. 3, one could conclude that the extent of reduction was not affected greatly by the presence of carbon dioxide, with the exception of the filter bag material. This could be an indication of a "fast" chemical reaction between carbon dioxide and the graphite lining to produce carbon monoxide, resulting in the partial pressure of carbon dioxide to reach such a small value that it had no significant effect on the reduction reactions. At an average cyclone temperature of 1773°K (1500°C), the equilibrium constant of the Boudouard reaction is about 12,150, indicating that nearly all the carbon dioxide will be reduced to carbon monoxide (given excess carbon is present and the reaction time is sufficiently long). The fact that carbon dioxide analysis was always small in these two sets of experiments suggests that the average residence time was long enough for the gasification reaction to approach completion.

Temperature effect

To evaluate the influence of temperature on the reduction of taconite, several experiments were conducted in which the input energy to the system was varied from 34 to 41 KW, depending on the temperature desired. Since the plasma

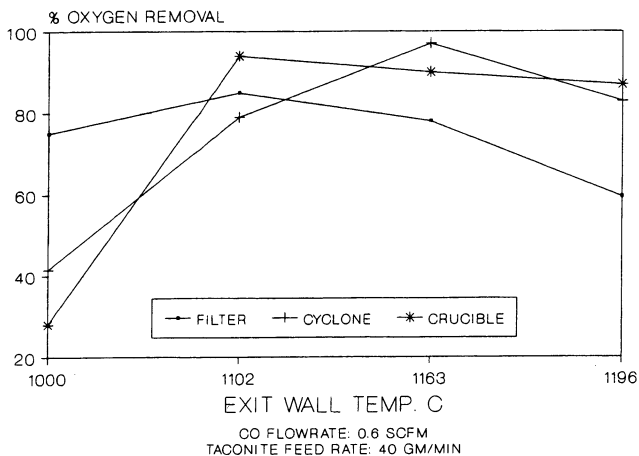


Fig. 4 — Oxygen removal vs. exit wall temperature.

varied with the input energy (i.e., with the plasma gas flow rate and the reactor average temperature). The average reactor temperature was varied between 1673-1883°K (1400-1610°C). In these experiments, the carbon monoxide flow rate was fixed at 0.175 m³/min (10.62 scfm), the taconite feed rate was 40 g/min and no carbon dioxide was injected to the cyclone. The percentage of oxygen removal from the taconite feed is shown in Fig. 4. As can be deduced from Fig. 4, at temperatures above 1773°K (1500°C), the degree of reduction does not change greatly with temperature, and below 1773°K (1500°C) the extent of reduction decreases rapidly as the temperature is lowered with the exception of the filter bag samples. The oxygen removal from the filter fines appears to remain constant up to an average temperature of 1823°K (1550°C). Above this temperature, the oxygen removal drops. One reason for this behavior is the significant difference in the residence time for these experiments. In addition, while the flow rate of carbon monoxide was fixed at 0.175 m³/min (0.62 scfm), its inlet partial pressure actually decreased with increasing temperature, due to the higher plasma gas flow rate (higher energy input requirements).

Carbon dioxide interaction with the lining

To determine the extent to which carbon dioxide reacts with the graphite lining, several experiments were conducted at different temperatures. The carbon dioxide flow rate was fixed at 0.011 m³/min (0.40 scfm), and neither taconite nor carbon monoxide were introduced into the reactor. The plasma torch input energy was varied between 32-40 KW, resulting in an average cyclone temperature between 1563-1775°K (1290-1502°C). The gas exiting the cyclone was continuously analyzed for carbon monoxide and carbon dioxide using the IR gas analyzer. These experiments were terminated when the IR reading indicated a constant gas composition. Figure 5 shows the amounts of carbon monoxide and carbon dioxide (moles/min) in the exit gas as a function of time.

The data indicate that it took ≈2 min. to reach steady-state conditions. In addition, the carbon dioxide composition in the exit gas was always less than 2%, even at the lower temperature of 1563°K (1290°C), and it dropped with increasing temperatures. At an average cyclone temperature of 1773°K (1500°C), almost all the carbon dioxide fed to the

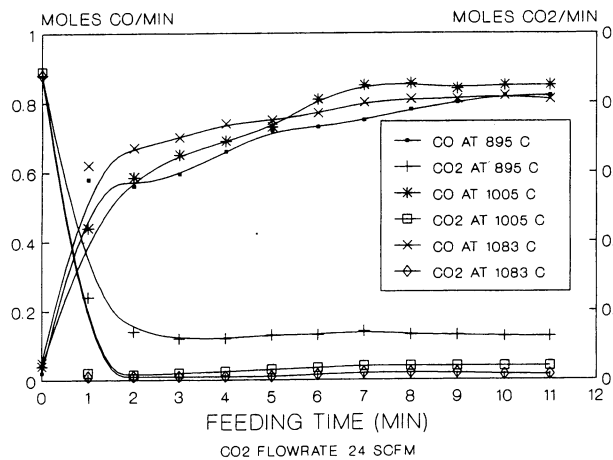


Fig. 5 — Exit composition of CO and CO₂ vs. time.

Taconite reaction with the lining

In a previous section, it was suggested that a large proportion of the taconite feed is melted and is partially thrown on the reactor walls by the swirling motion of the plasma gas. The melt reaching the wall forms a thin liquid film and flows downward, mainly by gravitational forces. Once formed, the liquid film reacts with the graphite, as well as the carbon monoxide in the gas, resulting in the higher degree of reduction for the material collected in the cyclone. To confirm this suggestion and to evaluate the degree to which the film interacts with the lining, several experiments were carried out at different temperatures. The taconite feed rate was constant at 40 g/min and no carbon monoxide or carbon dioxide were injected to the cyclone. The average cyclone temperature was varied between 1658-1893°K (1380-1620°C).

The degree of reduction increases rapidly with temperature, and, at 1893°K (1620°C), no significant difference could be seen between the iron analysis whether carbon monoxide was fed or not. The steady state carbon monoxide composition in the exit gas was ≈8.7% CO by volume when the operating temperature was 1893°K (1620°C), and no carbon dioxide was detected either on the gas chromatograph or on the IR. This corresponds to 0.54 moles/min of carbon monoxide being generated by the reduction reactions and suggests that the reaction between graphite and molten iron oxides is significant enough to influence the degree of reduction and the reaction kinetics.

Nickel oxide experiments

The flow pattern of gases in a cyclone reactor is believed to be of plug-flow type (Bradly, 1959, Lang, 1982, Li, 1982, Lede, 1989). Meanwhile, the behavior of the reacting particles depends on several factors including the gas flow rate, the particle size and size distribution, and the particles feed rate in comparison to the gas flow rate. In their study, Li et al. (1989) concluded that the solid phase exhibited plug-flow behavior at higher gas flow rates and showed some back mixing when the gas flow rate was decreased. He also showed that there is a region of mixing near the entrance of the cyclone that provides very intimate mixing between the feed and gases. In the experimental system employed, this region is believed to form a liquid film covering

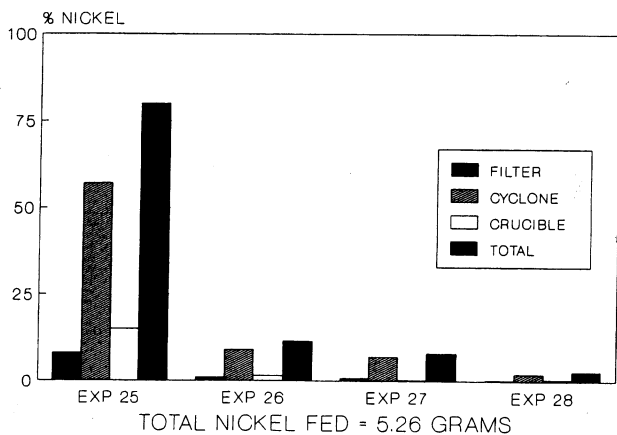


Fig. 6 — Nickel analysis in experiments 33 through 36.

reactor with the flowing gas. To better understand the flow behavior of the liquid film and the fines, experiments were conducted in which 10 g of finely-divided nickel oxide were thoroughly mixed with 990 grams of taconite powder to give a 1.0% NiO, 99.0% taconite mixture. The mix was used in one experiment only, and the nickel analysis was followed in four subsequent tests. Nickel appeared in each product fraction and was determined using a Perkin-Elmer Atomic Absorption spectrophotometer (Model 2380). The experimental data is shown graphically in Fig. 6. Approximately 80% of the nickel fed into the reactor appeared in the product that was collected in the first experiment. Almost all of the nickel fed into the reactor discharged by the conclusion of the fourth experiment.

Although no nickel was fed into the reactor after the first experiment, the filter bag fines continued to contain nickel in decreasing amounts. This could have resulted from fines being trapped in the filter bag when nickel was fed into the reactor but not completely removed from the bag. The crucible product typically showed slightly higher nickel analysis than that of the cyclone.

The data presented in Fig. 6 suggest that the behavior of the liquid film could be of plug-flow type with some back mixing. As mentioned earlier, a large fraction of the solid feed is immediately thrown onto the wall as molten droplets by the swirling motion of the gas. These droplets either reach the wall and form a molten film or flow in spirals in the vicinity of the wall. The portion that forms a liquid film would travel downward under the influence of gravity, and, due to the wall roughness and the high viscosity of the melt, it does not exit the cyclone within one experimental run. Meanwhile, the molten droplets reach the surface of the conical section and collect there as solid material once the temperature drops below the melting point. These factors, as well as the difficulty in collecting all the product from the cyclone, led to the observed 20% of the nickel being held up in the system.

Plasma interactions with the reactants

As described earlier, the taconite powder and the gaseous reactants were injected axially just ahead of the plasma flame. Although the plasma torch was inserted 0.11 m (4.5") inside its port (the total length of the port is 0.25 m (10")), it was not possible to completely eliminate the interactions

Table 2 — Carbon analysis in several product samples

	Percent carbon		
	filter	cyclone	crucible
EXP 26	0.412	0.030	0.569
EXP 28	0.756	0.059	0.326
EXP 21	0.650	1.277*	3.800**

* Sample taken from the material in direct contact with the wall.

** Sample taken from spherically shaped material

entered the cyclone was in the range of 3273-3723°K (3000-3500°C). In other words, the gas possessed high thermal energy such that it was possible to melt the taconite feed almost instantly. In addition, it is known that hematite (apparently 25.81% in the fines based upon the elemental analysis provided by LTV) decomposes to magnetite and oxygen at 1733 k (1460°C). Meanwhile, carbon dioxide dissociates to oxygen and carbon monoxide at about 3253°K (2980°C). It is believed that the taconite feed is at least partially decomposed to iron, wustite and oxygen upon its immediate contact with the plasma flame. The oxygen released combines with the graphite lining to form carbon monoxide. It is also possible that this oxygen could react with carbon monoxide to form carbon dioxide, which would then diffuse to the lining surface and reacts with the graphite to regenerate carbon monoxide. This suggestion is supported by the thermodynamic predictions (Abdel-latif, 1991) and, more importantly, by the experimental evidence obtained by analyzing the material that was found to have accumulated on the plasma torch front electrode and its water guide.

Samples collected from several experiments were analyzed for total iron. Iron was always greater than 80%, and the oxygen removal was more than 59%. This corresponds to approximately 34% metallic iron, 61% wustite and 5% silica and other impurities. It is believed that the high degree of reduction of this material could not have resulted from the reduction with carbon monoxide only and that the dissociation of taconite contributed to the high degree of reduction observed.

Carbon analysis

Several samples were sent to the LECO Corporation in St. Joseph, Michigan, for the determination of total carbon. The results obtained are presented in Table 2. The carbon analysis in the filter powder is relatively high (0.41% to 0.76% C) and is believed to have resulted from the abrasion of the graphite lining while the reactor was being heated to the desired temperature. The crucible material contains 0.33% to 0.57% C compared to 0.03% to 0.06% C in the cyclone product. The apparent higher carbon analysis in the crucible material could be due to some of the carbon fines being collected in the crucible during the heating period with this material consisting of the spherically-shaped particles that melted and passed out of the reactor while the cyclone temperature was increasing and stabilizing at the desired point. In other words, these spheres spent extended periods of time in contact with the graphite, and, given the operating temperatures employed, a relatively higher amount of dissolved carbon in these samples is not surprising.

The carbon composition in the cyclone product can be considered to be very low and insignificant. Except for that portion in the immediate contact with the lining, the cyclone

the gas phase, and does not come in contact with the graphite.

Conclusions

A cyclone reactor system for melting and partial reduction of particulate taconite concentrate was designed and operated. Reduction experiments showed that the carbon gasification reaction was extremely fast, such that carbon dioxide feeding exerted no significant influence on the final reduction of the taconite, and changing the CO-inlet partial pressure had little influence on the final degree of reduction.

The average reactor temperature greatly influenced the final degree of reduction. Oxygen removal increased with temperature up to a certain point, and then it either remained constant or decreased with a further increase in temperature. This is believed to be due to the significant difference in the average reaction time.

Solid carbon reaction with the molten iron oxides and the almost instantaneous melting and dissociation of taconite particles, as they encountered the intense plasma flame, contributed to the high degree of reduction reported.

The behavior of the liquid film approaches plug flow, with little back mixing. At the entrance of the cyclone reactor, there is a high degree of mixing that leads to the intimate contact of the feed prior to the film formation.

Future improvements in the reactor should include the use of a nitride-bonded silicon carbide liner to eliminate the interaction and to improve wear resistance, and should include the modification of the discharge geometry to allow the drainage of the molten material from the bottom of the reactor. Further research should evaluate the use of dried coal fed with the taconite and oxygen and an oxygen enriched coal-fired burner in place of the plasma torch.

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