7.1 Introduction

The two important parameters play the vital role in the sustainability of the electric steel making process, i.e. plant economy as well as environmental consideration. The process economy in transferred arc plasma (TAP) furnace depends mainly on consumption of energy and electrode. Regarding environmental concern, mostly associated with the generation of sound, dust, fumes and gasses, etc.

In the economics of electric steelmaking process, two factors are responsible for their ease and accuracy. i.e. the specific energy consumption and graphite electrode consumption. It is important to realize that these items also depend on many other process variables.

Conventionally, in electric arc furnace melting, 304-524 kWh/t electrical energy is required only for melting purpose (IISI, 1998). Depending upon the melt shop operation, about 60 to 65% of the total energy is electric and the remainder being chemical energy arising from the oxidation of elements such as carbon, iron, silicon, etc. and the burning of natural fuels with oxy-fuel burners. About 53% of the total heat energy leaves the furnace with the tapping of molten steel, while the remaining goes to the slag, waste off-gases, and cooling systems. Just a decade ago tap-to-tap times had brought down from over 2 hours to 70-80 minutes due to the efficient melt shops operation. Continuing advancements in the EAF technology now make it possible to melt heat of steel in less than one hour time with electric energy consumption in the range of 360 to 400 kWh/ton. EAF operations are utilizing scrap preheater such as in the CONSTEELQ Process. Now, most of the new EAF shop aims for keeping tap-to-tap time in between 50-60 minutes. These times are rapidly approaching towards the melting time of the basic oxygen furnace operations used in integrated steel mills.

Several authors have studied to know the mechanism of electrode consumption. Electrode consumption classifies into two broad categories. At the tip of the electrode column, due to the rapidly traveling of arc spot, in slag and metal without abruptly shortening the length of the column. Similarly, oxidation of the surface of the electrode causes gradual tapering in the electrode. The consumption through arc tip occurs mostly when power on, whereas erosion of electrode surface happens when electrodes are in hot condition. This combination establishes the electrode consumption and is manageable to some degree by smooth furnace practice (Schwabe, 1972). Protective coating over the surface of graphite electrode decreases the cost of electrode consumption. (Kurzeja, 1976). Electrode consumption also affects the plant economy due to the cost of graphite electrode consumption which is ~10% of the total production cost in the electric arc furnace (Edneral and Afanas' ev, 1979).

For promoting the sustainable development of the steel industry, lower energy consumption, as well as less acoustic, dust, fumes, gasses emission, is mandatory. Towards the development of environmental control, steel manufacturers are paying more attention nowadays due to the tight legal framework of the government. It was aware since the last 1974, when a first specialized conference was held on the subject in Tokyo, by International lron and Steel Institute. In this meeting, it was pointed out that due to environmental awareness in public, the steel producers were prepared to invest in antipollution measures. Many government and non-government organizations of the world have become conscious about environmental problems and are doing their best to get the anti-pollution laws enforced with more strictness.

Acoustic emission during electric arc melting is one of the problems for those who work near and around the furnace area. The effect of noise on human beings was summarized by Willis (Willis, 1978). The arc furnace area is characterized as noisy area since the sound level exceeds 100dB (Nedovato, 1977). For minimizing the noise hazards, various methods are employed e.g. ear muffs, sound proof control cabins for operations, construction of an enclosing chamber (doghouse) with control systems located outside the doghouse (Brand, 1981). In this context, plasma arc system could be attractive means for melting, which works at relatively lower noise level as reported by several authors (Knopper, 1985; Neuschutz et al., 1985; Sinha and Gupta, 1993; Sommerville et al., 1987).

The electric arc furnace is known as a significant polluting emissions generator, having a strong impact on the environment (Best and Pickles, 2001; A Ioana, 2007). The largest polluting emissions of the EAF (Chi et al., 2008; Hara, 1997; Huber et al., 2000) are:

- The dust emission through exit gas resulted during charging base materials and during operation of steel melting, refining, alloying which contain heavy metals (Cr, Ni, Zn, Pb, etc) and can reach values upto15 kg/t steel (Antrekowitsch and Antrekowitsch, 2003).
- The gasses resulted from the refining reactions, which mainly contains CO, CO_2, SOx and NOx (A. Ioana, 2007a).

From the total polluting emissions, over 90% are generated during the operations of refining. These emissions have a high content of oxides of iron, manganese, aluminum and silicon as well as heavy metals oxides (Ni, Cr, Cd, Pb, Cu) (A. Ioana, 2007b).

In the present investigation, an effort has been made to note the consumption of electrical energy, graphite electrode as well as the generation of sound level, dust emission, etc. of the laboratory plasma arc unit (2 kg capacity) during melting under normal arc and while switching over to plasma arc respectively.

7.2 Experimental

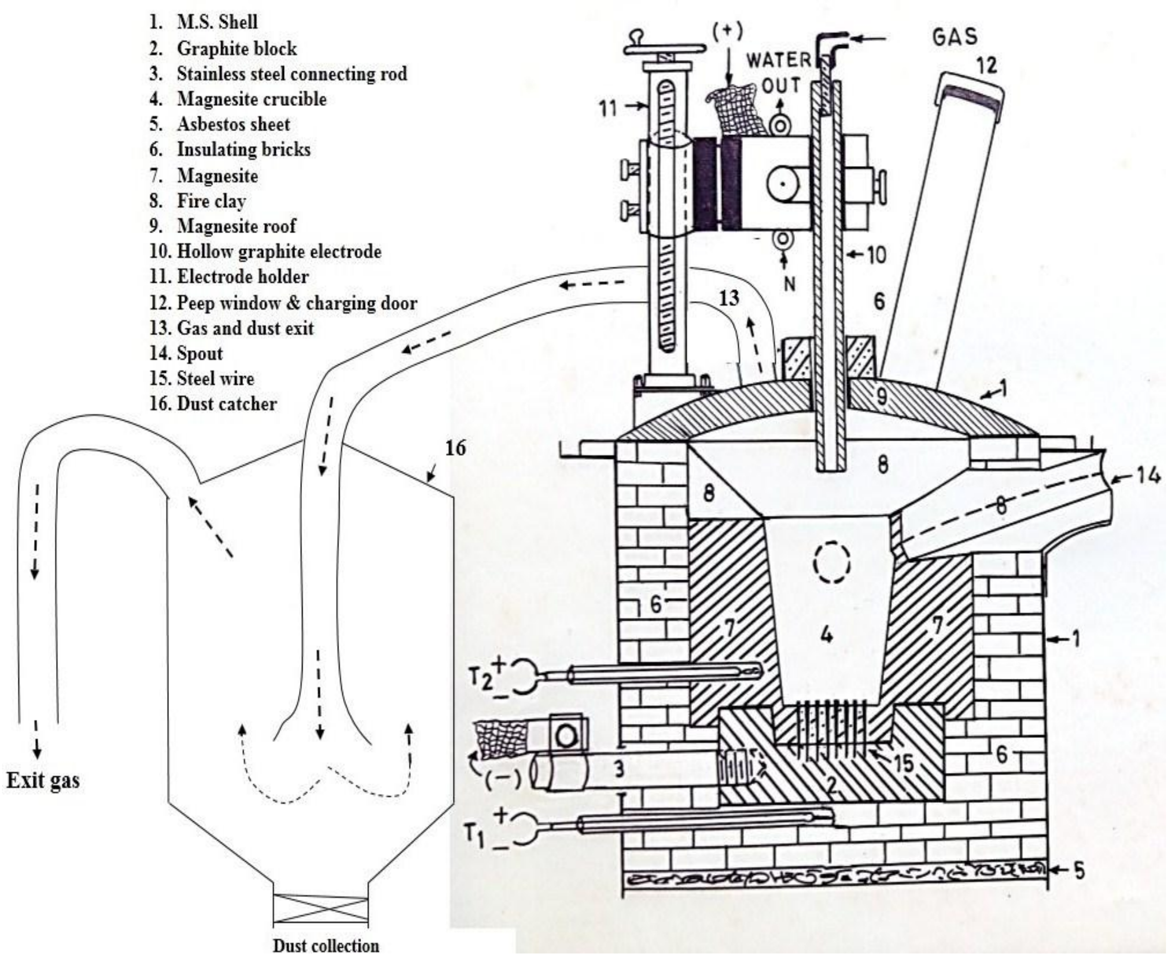

Figure 7. 1 Dust collection assembly

These observations present about the issues come out from the studies carried out during smelting reduction of iron ore slime and bottom ash under plasma environment. For the energy consumption record, reading from the energy meter was noted. Graphite consumption was recorded by measuring the weight losses occurred for particular tapping. For doing the experiments, one extra attachment was fitted at the gas exit point for the collection of dust and gas as shown in Figure 7.1. Dust generation was calculated for the every tapping and analyzed for their chemical composition by XRF analysis. Carbon content was determined by doing the proximate analysis. The sound level was measured by decibel meter; Sound Meter Pro software was used for the continuous measurement of the noise level.

7.3 Results and Discussions

7.3.1 Economic parameters

As described in above section 7.1 that the production cost of electric arc furnace is dependent on the consumption of energy, electrode, and lining material. In present studies, several heats in one campaign were performed, that’s why the consumption of lining material for each heat could not be determined separately. The energy and graphite electrode consumption are described in following sections.

In the present study, only power consumption in the form of electrical energy was calculated. Data for consumption of energy and graphite electrode is shown in Table B.8 of Appendix-B. The effect of different parameters on energy and graphite electrode consumption are described in the following sub-sections.

7.3.1.1 Arc type

The trend of energy and graphite electrode consumption for heat number 21, 03, 19 as well as 22, 04, 20 at different arcing condition (i.e. normal arc, nitrogen plasma, hydrogen plasma) are shown in Figure 7.2(a,b) for charge containing bottom ash as well as mixture of bottom ash and iron ore slime respectively. The energy consumption in case of the normal arc was maximum as compared to plasma arc system. As compared to nitrogen plasma arc, energy consumption in hydrogen plasma was least. It may be due to the combined effect of heat production (i.e. ionization and combustion) in hydrogen plasma was more as compared to nitrogen plasma (i.e. ionization only) and the normal arc (only dissociation of species present in air). Whereas, the graphite electrode consumption in case of the normal arc was maximum as compared to nitrogen plasma arc system. But in the case of hydrogen plasma arc, graphite consumption was increased as compared to nitrogen plasma. It may be due to the nitrogen plasma arc was produced the smoother arc, less flickering and creates an inert atmosphere, resulted in less graphite consumption. But in the case of hydrogen plasma, due to high temperature, it may be reacted with the carbon of graphite electrode to form methane gas, resulting in more consumption of electrode as the phenomena were discussed during the operational trial of fabricated TAP furnace as mention in Section 5.4.2.5. Increasing iron ore slime content in fixed weight of charge material means the iron oxide increases in the charge. The requirement of energy for reduction of iron oxide was less in comparison to silica or alumina. Therefore a substantial decreased in energy, as well as graphite electrode consumption, were observed for the mixture of bottom ash and iron ore slime as compared to only fixed weight of bottom ash charge.

7.3.1.2 Crucible material

Energy and graphite electrode consumption trends for heat number 03, 07 and 04, 08 at different types of crucible lining (i.e. magnesite and graphite) are shown in Figure 7.3(a,b) for charge containing bottom ash as well as a mixture of bottom ash and iron ore slime respectively. Graphite is a good conductor of electricity but the bad conductor of heat. Due to better electrical conductivity, the arc became more stable.

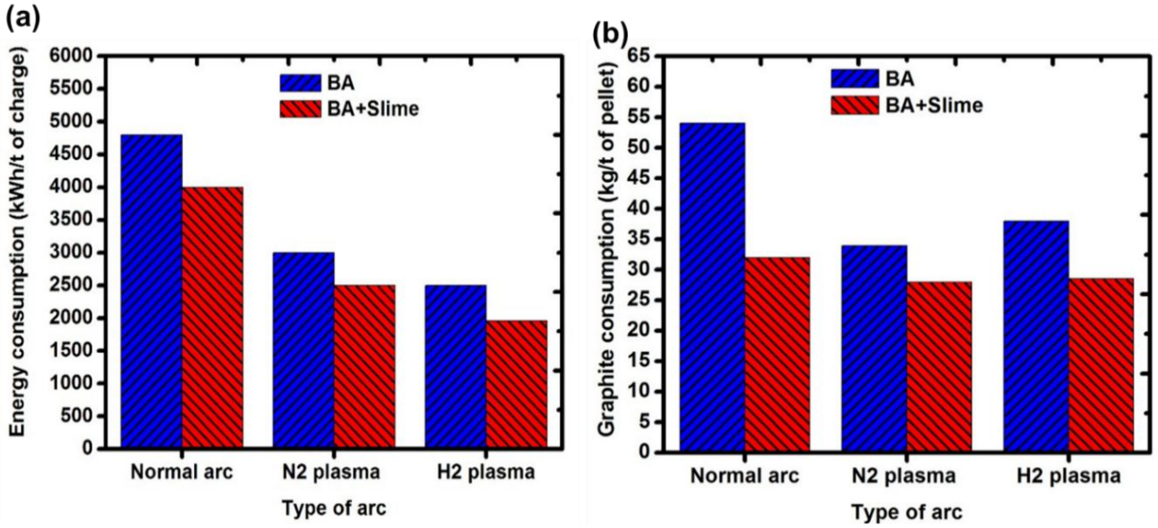

Figure 7. 2 Effect of arcing type on (a) energy and (b) graphite electrode consumption

Therefore steady state arcing was observed. The thermal conductivity of graphite is less than magnesite which was decreased the heat loss through lining material. These combined effect may be resulted in lesser energy and graphite consumption in case of graphite crucible as compared to the magnesite crucible.

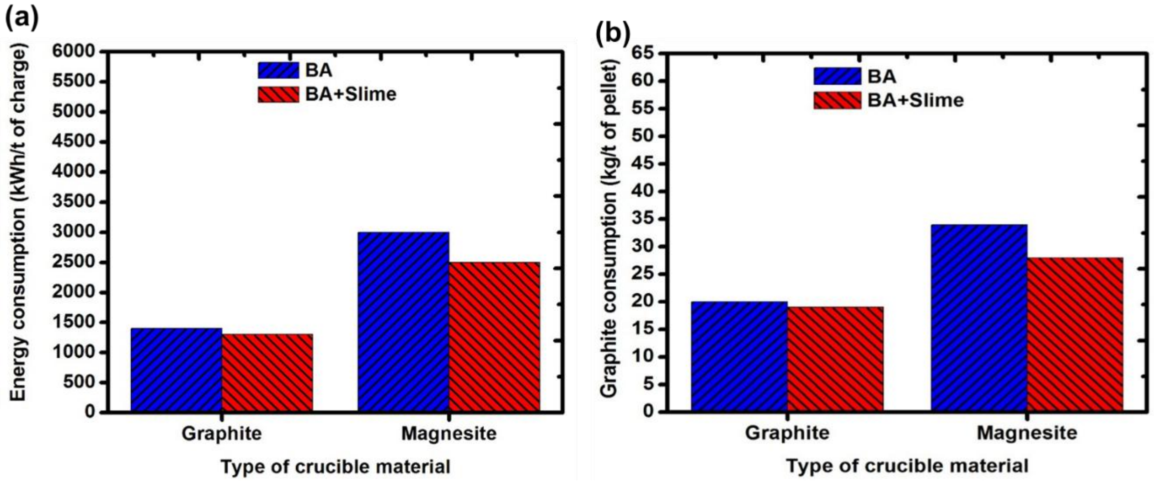

Figure 7. 3 Effect of crucible lining material on (a) energy and (b) graphite electrode consumption

7.3.1.3 Forms of charge material

Energy and graphite electrode consumption trends for heat number 01, 07 and 02, 08 at a different form of charge (i.e. pellets, powder) are shown in Figure 7.4(a,b) of charge containing bottom ash as well as a mixture of bottom ash and iron ore slime respectively. In the case of the powder charge, the arc zone was surrounded efficiently as compared to pellet charge which was decreased the heat loss. The reduction time for pellets charges became more as compared to powder charge. It is due to powder charges having more surface area, requires less time for the reduction. Therefore, the combined effect of both factors decreased the energy and electrode consumption in the case of powder charging.

7.3.1.4 Reductant reactivity

Energy and graphite electrode consumption trends for heat number 03, 09, 11 and 04, 10, 12 at varying reactivity of reductants are shown in Figure 7.5(a,b) for charge containing bottom ash as well as a mixture of bottom ash and iron ore slime respectively. With increasing the reactivity of the reductant, the reduction of oxides was enhanced, which decreased the reduction time. Therefore, increasing reactivity has reduced the energy and graphite consumption.

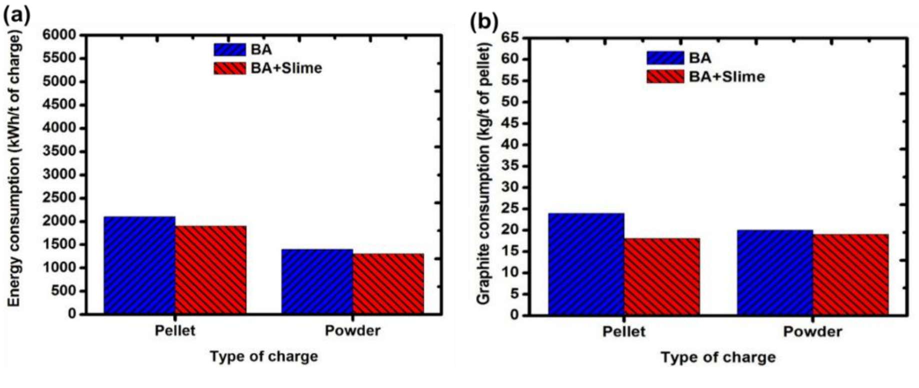

Figure 7. 4 Effect of charge form on (a) energy and (b) graphite electrode consumption

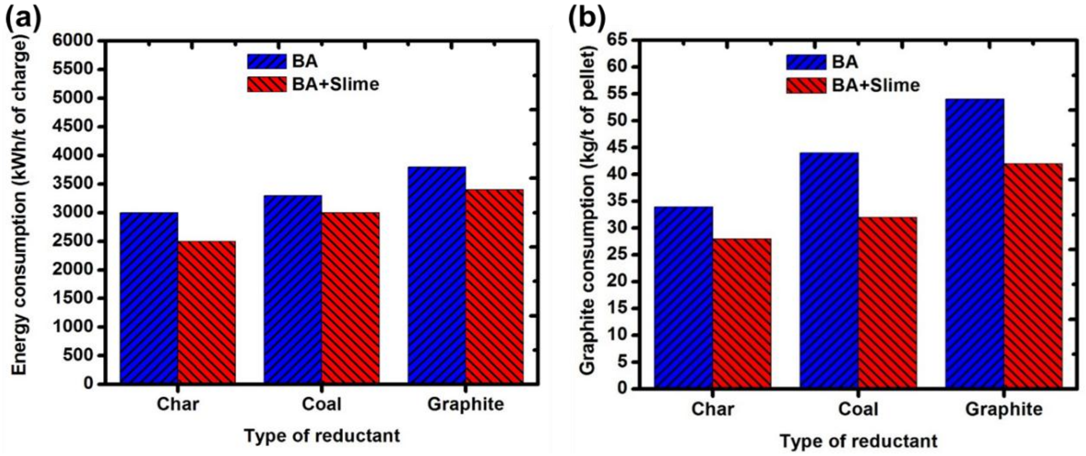

Figure 7. 5 Effect of reductant reactivity on (a) energy and (b) graphite electrode consumption

7.3.1.5 Stoichiometry carbon content

The trends of energy and graphite electrode consumption for heat number 13, 03, 15 and 14, 04, 16 at different stoichiometry ratio of carbon (i.e. half, normal and double) are shown in Figure 7.6(a,b) for charge containing bottom ash as well as mixture of bottom ash and iron ore slime respectively. With increasing the stoichiometry carbon, the energy consumption was decreased slightly. It may increase carbon content which enhanced the reduction rate, resulted in lower energy consumption. When the carbon level was lower the stoichiometry, then the required carbon content may be supplied by the carbon of graphite electrode. This process took time resulting in a slight increase in energy consumption and also graphite electrode consumption.

7.3.1.6 Charge layer thickness

Energy and graphite electrode consumption trends for heat number 05, 03 and 06, 04 at different charge layer thickness (i.e. half, normal) are shown in Figure 7.7(a,b) for charge containing bottom ash as well as a mixture of bottom ash and iron ore slime respectively. The arc zone was covered effectively by increasing charge layer thickness, which reduced the heat loss, resulting completion of reduction in less time. That's why the energy and graphite electrode consumption may be reduced.

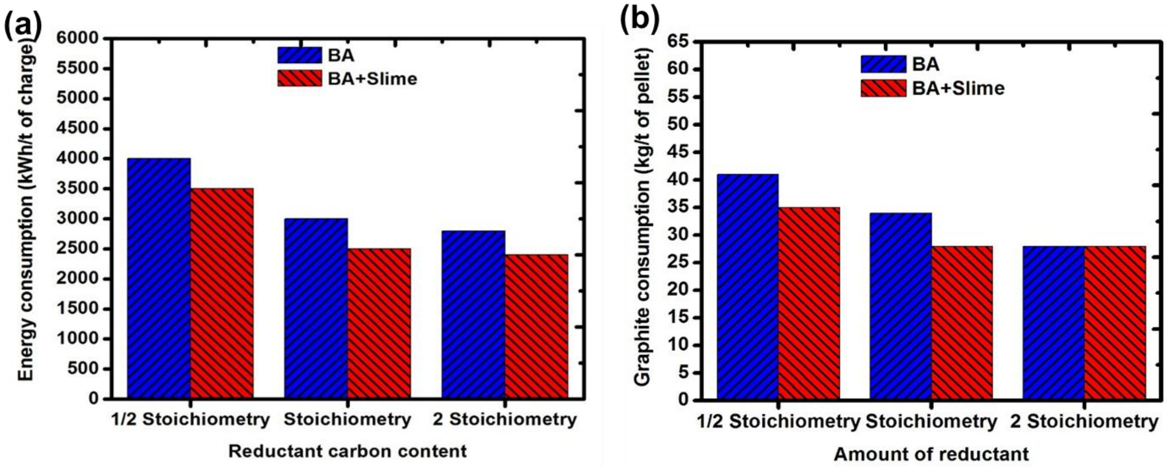

Figure 7. 6 Effect of stoichiometry on (a) energy and (b) graphite electrode consumption

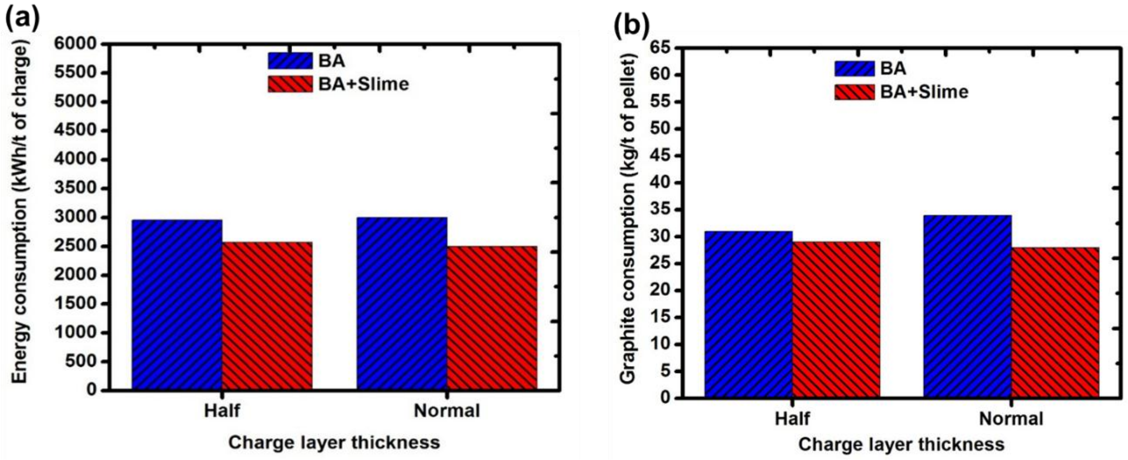

Figure 7. 7 Effect of charge layer thickness on (a) energy and (b) graphite electrode consumption

7.3.1.7 Reducing agents

Energy and graphite electrode consumption trends for heat number 17, 03,19 and 18, 04, 20 at different reducing agent (i.e. hydrogen, nitrogen+carbon, hydrogen+carbon) are shown in

Figure 7.8(a,b) for charge containing bottom ash as well as a mixture of bottom ash and iron ore slime respectively.

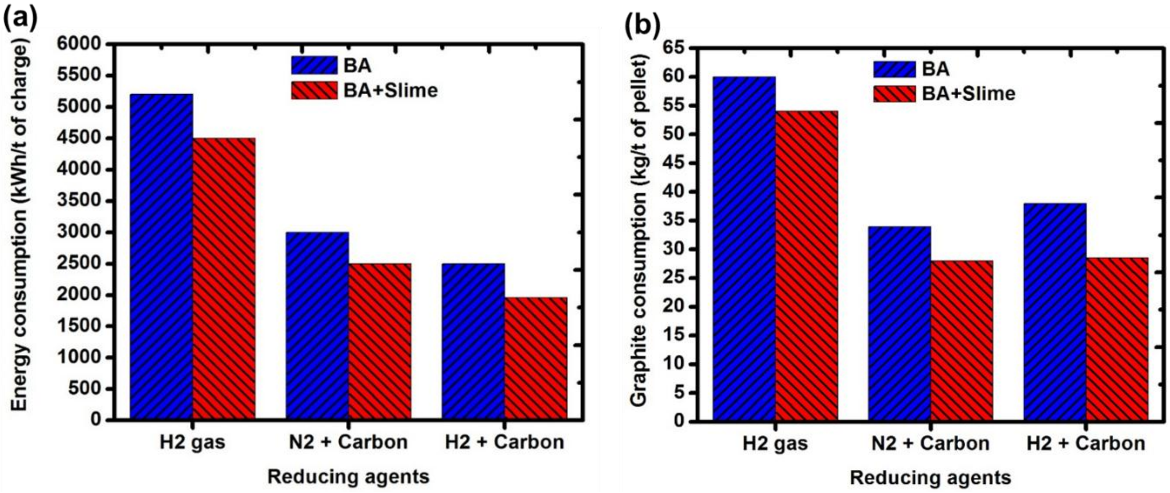

Figure 7. 8 Effect of reducing agents on (a) energy and (b) graphite electrode consumption

As mentioned in previous section 6.3.1.8 of chapter 6, that the reducing gas (i.e. hydrogen) did not take part much in the reduction of oxides in the absence of carbon. Therefore, the primary fused oxide remained as a slag over the melt, which increased the resistance of the path. For that reason, the current input was slightly increased for generation of heat to maintain the liquid pool, resulting increased energy and graphite electrode consumption.

7.3.2 Environmental parameters

Sustainable development in the production of electric arc furnace steelmaking is considered for minimizing the acoustic emission, dust emission, gas emission, etc. In the present study following parameters like sound generation, dust generation, and their composition variation was noted.

7.3.2.1 Sound generation

Noise level variation was recorded at different operating parameters as mentioned in following subsections. Conventionally up to scrap melting stage, the normal arc with solid electrode was used, followed by a hollow electrode for generation of different kinds of plasma.

a) Arc type

It was observed that plasma arc decreases the sound level as compared to normal arc as discussed in the previous chapter 5 of section 5.4.2.4. It is due to the generation of a smooth path for electrons movement in the plasma environment. It was also observed that the variation in sound level does not occur much in the case of bottom ash charge as well as bottom ash and iron ore slime mixture (Figure 7.9).

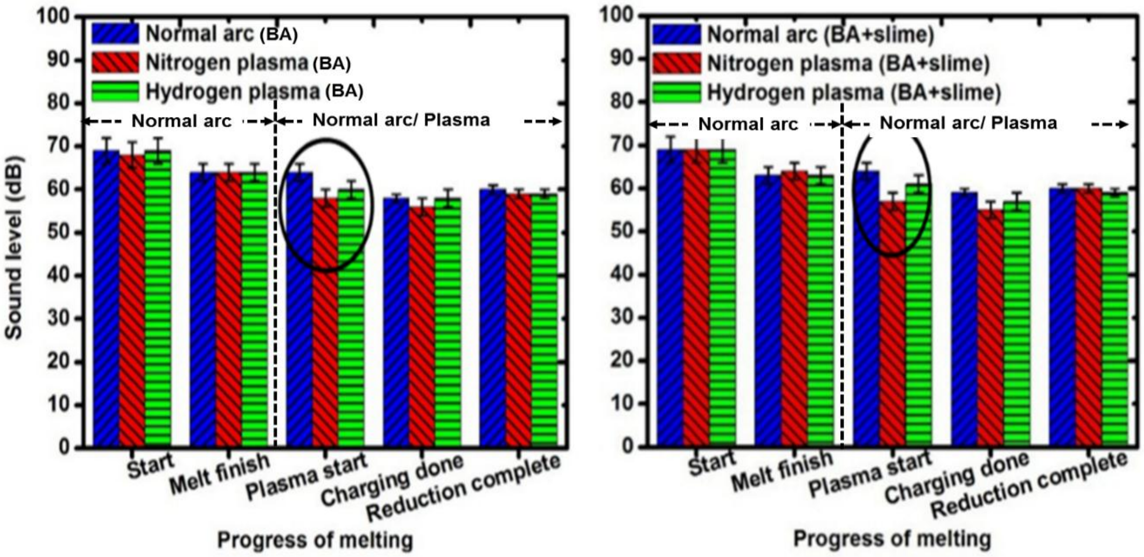

Figure 7. 9 Effect of arcing type on sound level

b) Crucible material

As mentioned above in the section 7.4.1.1 during energy and graphite electrode consumption, the graphite is known for good conductor of electricity; hence arc current can quickly pass throughout the graphite crucible. In the case of magnesite crucible, only embedded steel nails were responsible for the passing of the electrical discharge. Therefore, sound generation in magnesite crucible was more than graphite crucible due to the restriction of passing current (Figure 7.10).

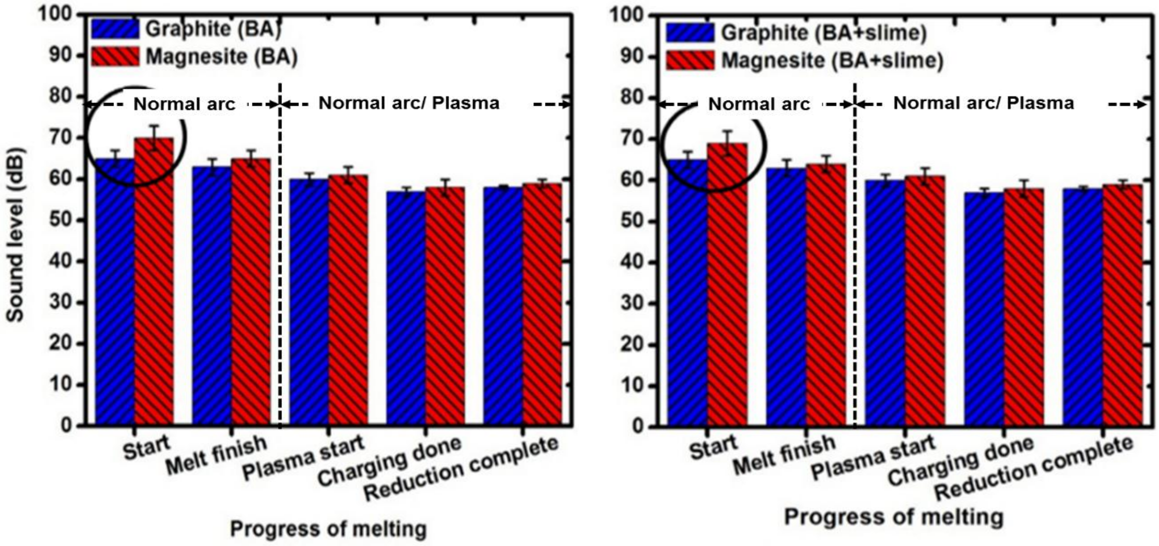

Figure 7. 10 Effect of crucible lining material on sound level

c) Forms of charge material

The sound level was decreased in case of powder charged material as compared to pellet during plasma operation as shown in Figure 7.11. It may be due to the powder charging, covered the arc zone effectively then pellet charge, resulted decreasing in sound level.

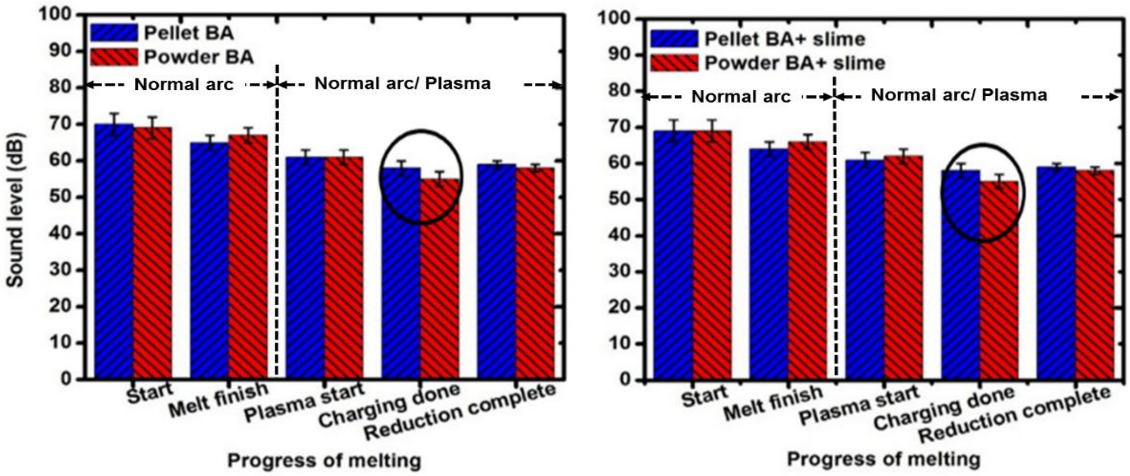

Figure 7. 11 Effect of charge form on sound level

d) Charge layer thickness

With increasing the charge layer thickness, decreased sound level was observed as shown in Figure 7.12. Increasing charge layer thickness which covered the arc effectively resulting reduced noise level.

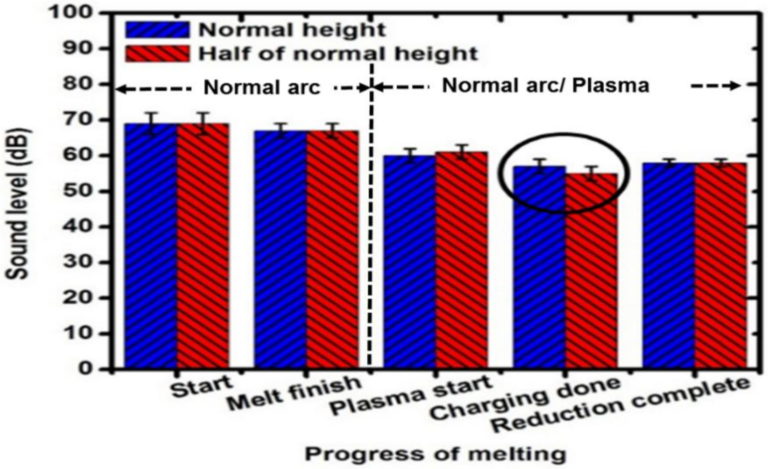

Figure 7. 12 Effect of charge layer thickness on sound level

7.3.2.2 Dust generation

The dust of the flue gas was collected from dust catcher was analyzed for different elements (i.e. Fe, Si, Al, Mg, Mn, C etc). These elements may come from the charge material, or from the product which forms after reduction and vaporization of charge (Si, Fe, Al, Mn) or lining material of crucible (Mg). The analysis of the various elements were correlated with the different phenomena happened during melting. Effect of the various parameters on dust generation is discussed in following sub sections.

a) Arc type

More dust generation was observed in the case of hydrogen plasma as compared to nitrogen plasma. Chemical constituents inside the dust for hydrogen plasma showed the increased amount of volatile metals like Mg, Al, etc with less amount of carbon and silicon. Therefore, it means that the constituents inside the dust are not coming directly from charge as dust, rather than it comes as vapor phases after reduction of the charge or furnace lining material. In previous chapter 6, section 6.3.1.3, it was shown that the less aluminium recovery in metals as well as in chapter 5, section 5.4.2.6 deals with the more magnesite lining erosion by hydrogen plasma. It means that Mg and Al content in the dust came from the reduction of magnesite lining and alumina content in charge material respectively (Figure 7.13).

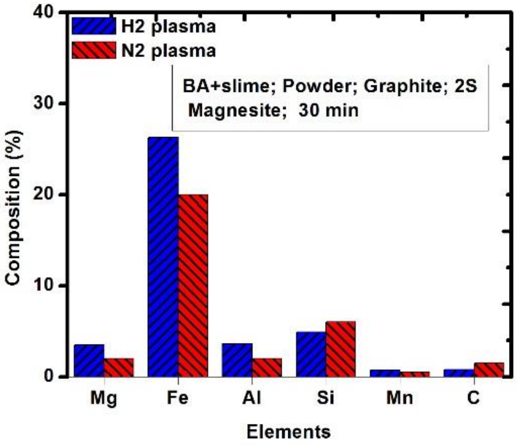

Figure 7. 13 Effect of plasma type on flue dust composition

b) Reductant content

The dust generation was increased in the presence of reductant content as compared to charge material having without reductant under plasma condition. The presence of a reductant formed a lot of fumes of volatile matters as well as gasses when comes into contact at high temperature. In hydrogen plasma, a high temperature and reducing atmosphere were generated, which may reduce the magnesite lining to magnesium and alumina to aluminium. Generated fumes may be carried away the vapor of metals (Al/Mg) easily to the dust catcher. Therefore, it may be the reason for the presence of increased content of these particular metals in case of charge material containing reductant under hydrogen plasma (Figure 7.14).

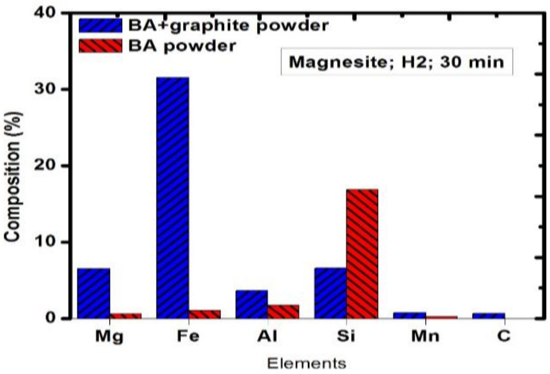

Figure 7. 14 Effect of reductant presence on flue dust composition

c) Reductant reactivity

The dust content at the dust catcher was increased by increasing reactivity of the reductant. Increasing reactivity of the reductant (more volatile material) forms a lot of fumes containing carbon. Therefore, the concentration of volatile metal was increased in the dust with increasing reactivity of reductant (Figure 7.15).

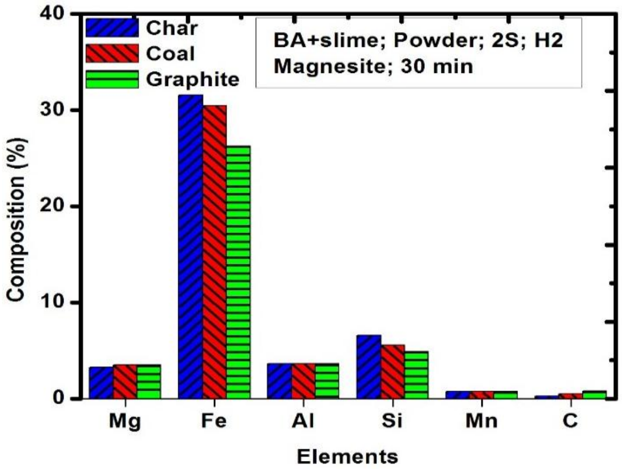

Figure 7. 15 Effect of reductant reactivity on flue dust composition

d) Charge material forms and composition

The dust generation was observed more in the case of powder as compared to pellets charge. The dust generation was decreased with the addition of iron ore slime in the charge (Figure 7.16)

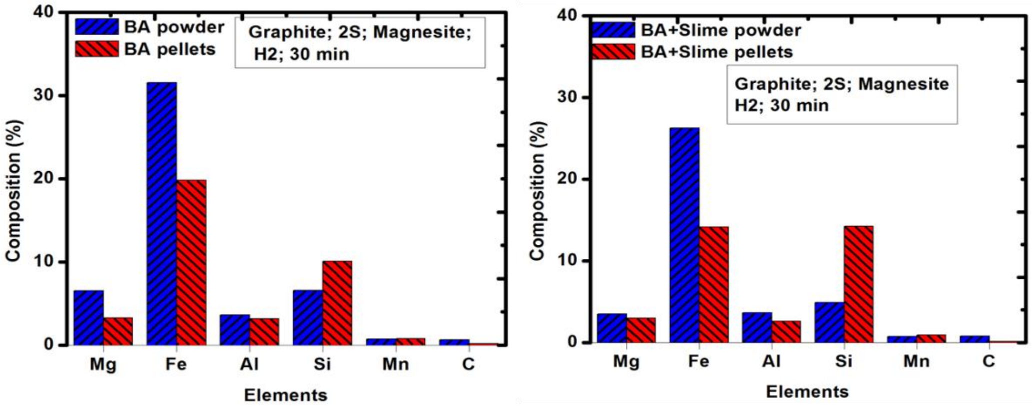

Figure 7. 16 Effect of charge materials form and composition on flue dust composition

Dust material was carried out due to arc pressure easily and increased the dust content. In the case of increased inter-particle space for pellet samples, the loss of more volatile metals was observed in previous chapter 6 section 6.3.1.5. It means the volatile metals for pellets sample quickly goes away through the exit gas and condense in dust catcher, resulting in increased volatile metals content inside the dust. Iron slime content forms liquid iron very fast in comparison to silica or alumina, resulting in easy absorption of aluminium vapor, therefore decreasing the content of these elements were observed in the dust (Figure 7.16).

7.3.3 Partitioning of elements recovered in metal, slag and gas

The composition of different elements inside metal, slag as well as dust were analyzed, and the partitioning behavior of each element was determined. The trends of partitioning of various elements are described in the following subsections.

7.3.3.1 Arc type

The oxides present in the charge material were reduced effectively under plasma environment as compared to normal arc. Therefore, the partitioning of metals in the slag was less. Less partitioning in slag was observed in the case of hydrogen plasma as compared to nitrogen plasma (Figure 7.17). Due to the high temperature of plasma, the losses of metals through the exit gas was more, resulting more partitioning of metals inside the dust and gas was observed.

7.3.3.2 Crucible material

Absorption of elements in metal bath in graphite crucible was shown more as compared to magnesite crucible. Therefore the partitioning of elements in metals was also more, resulting less partitioning of elements in dust and gas was observed. Magnesium content in slag and metals was not observed in the case of graphite crucible; therefore, it could be concluded that 100% magnesium in slag and dust came entirely from erosion of magnesite crucible lining (Figure 7.18).

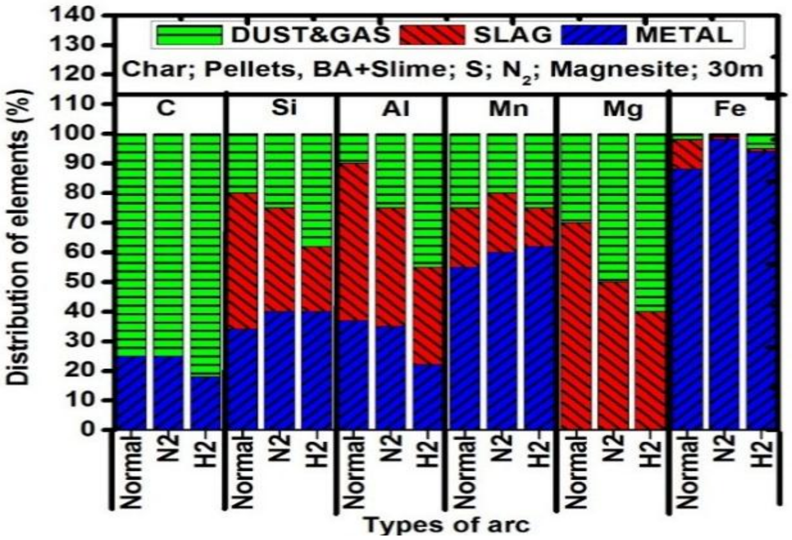

Figure 7. 17 Effect of arc type on partitioning of metals

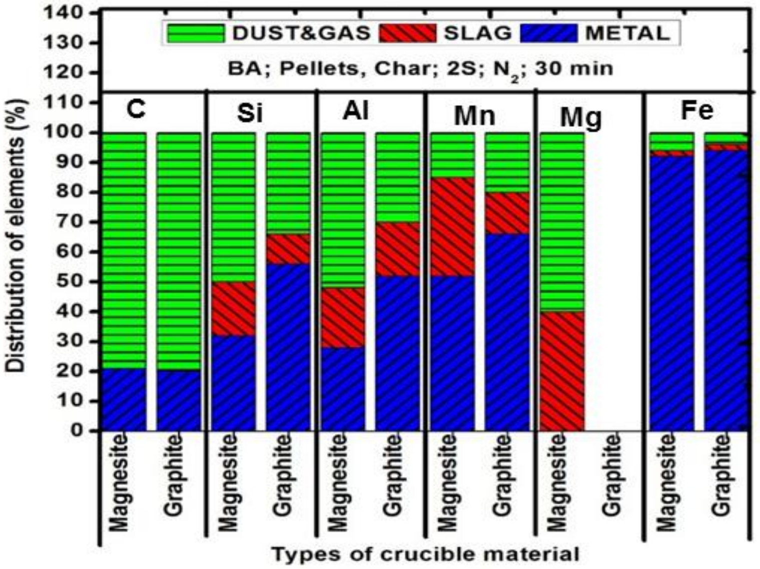

Figure 7. 18 Effect of crucible lining material on partitioning of metals

7.3.3.3 Charge forms

It was discussed in the previous chapter 6 section 6.3.1.5 that the more recovery of elements in metal was observed in the case of powder charge. Therefore, partitioning inside the metals was increased for powder charge material as compared to pellets. The reduction time in case of pellet charging was more because it takes more time due to its compacted structure. In the meantime, the highly reactive reductant exhausted without reacting completely. Therefore, unreduced oxides were entered into the slag phase and increased their partitioning. In the case of pellets charge, due to increased inter-particle spaces, partitioning of elements was more in dust and gas as compared to powder charge for volatile elements like aluminium, magnesium, carbon, etc. (Figure 7.19).

7.3.3.4 Reductant reactivity

Increasing reactivity of reductant enhances the recovery of elements inside the metals as previously discussed in section 6.3.1.2 of chapter 6. Therefore, the partitioning of elements in the metal was increased with increasing reactivity. Reduced reactivity of reductant (such as graphite) took more time for reduction of oxides in the meantime some part of the unreduced oxides may join in the slag. Therefore the partitioning of elements in slag may be increased with decreasing reactivity of the reductant. Reduced reactivity of reductant (such as graphite) was not exhausted easily and existed in contact with liquid slag-metal which increased the level of carbon in the molten metal. That’s why the carbon content in metal was increased for graphite reductant. Therefore the partitioning of carbon in metal was increased for less reactive reductant (Figure 7.20). The increased generation of fumes was observed in the case of increasing reactivity of reductant which was carried away with dust particles easily by arc pressure, resulted in increased partitioning of elements inside the dust.

7.3.3.5 Stoichiometry of carbon

The increased recovery of elements was observed for increasing carbon content in the charge mix as previously discussed in section 6.3.1.4. of chapter 6.

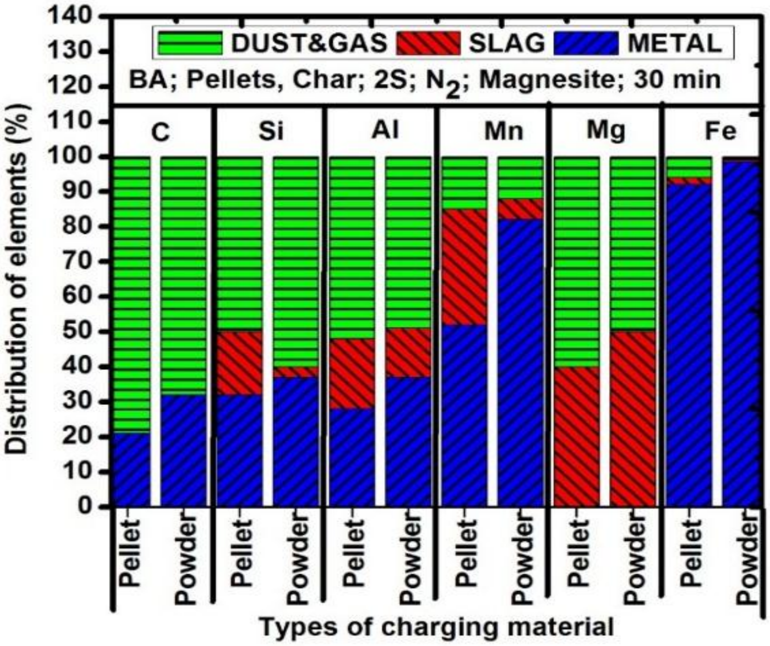

Figure 7. 19 Effect of charge form on partitioning of metals

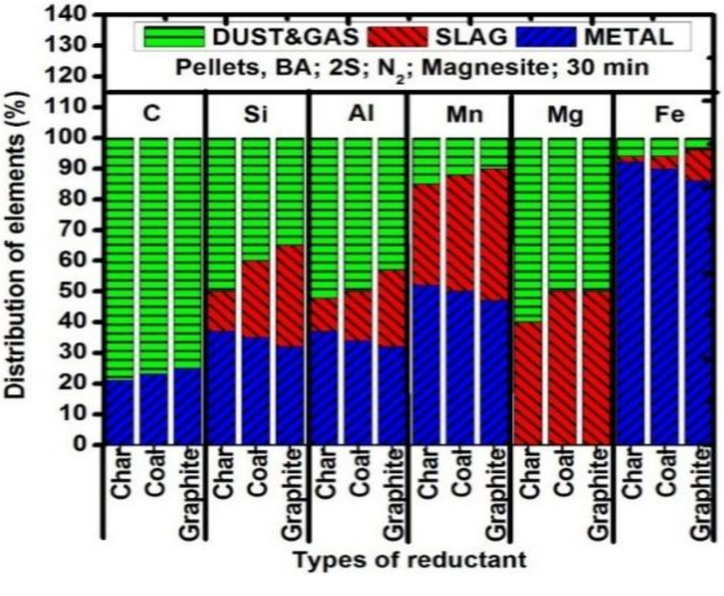

Figure 7. 20 Effect of reductant reactivity on partitioning of metals

Therefore the partitioning of elements in the metal was enhanced for more carbon content. More carbon content of reductant was absorbed inside the metals, with increasing stoichiometry, resulting in more carbon partitioning in metal. At below stoichiometry of carbon, oxide presents inside the dust could not sufficient to reduce the oxides. That's why, it entered into the slag, resulting in the increased partitioning of elements in the slag. Generation of fumes was increased with increasing the carbon content which may carry away with the dust particles along with arc pressure. Therefore, the partitioning of the elements was increased inside the dust and gas (Figure 7.21).

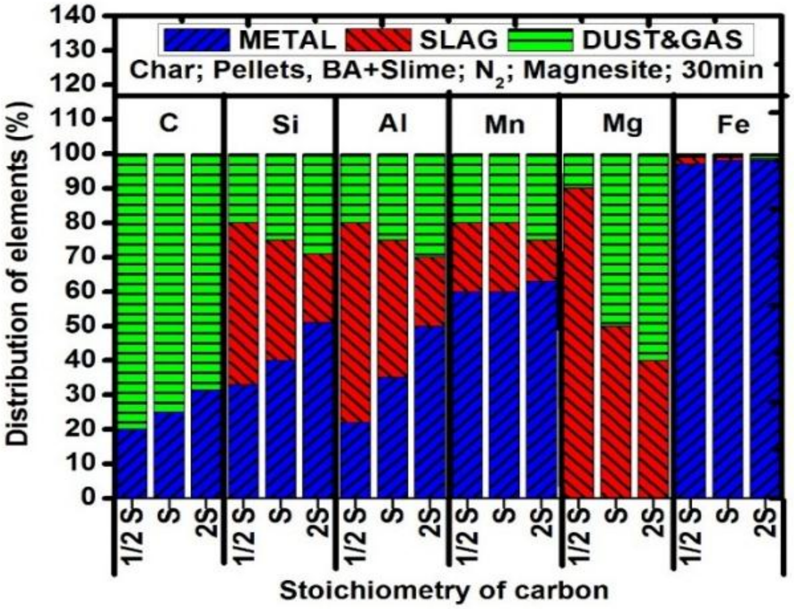

Figure 7. 21 Effect of stoichiometry carbon on partitioning of metals

7.4 Conclusions

Based on the above studies, following conclusions may be drawn:

1. The least energy consumption was observed in the case of plasma arc smelting in comparison to normal arc due to the generation of more heat by ionization of gaseous molecules at the arc zone.

   Graphite crucible decreases the energy consumption due to excess carbon dissolution in the iron melt through graphite crucible accelerates the reduction reaction.

Graphite crucible material, as well as powder charge, reduces the heat loss of reaction chamber by conduction, convection and radiation which is responsible for decreasing the energy consumption.

Increasing reactivity and stoichiometry carbon increase the reduction reaction hence reduced the energy consumption.

2. The graphite electrode consumption follows the similar trends as per energy consumption in all the case, except use of arc type. In the case of nitrogen plasma, least graphite electrode consumption was observed, whereas, slightly increased graphite electrode consumption due to reaction with hydrogen was noted in the case of hydrogen plasma.
3. Powder charge, increased charge bed height, covers the arc zone which decreases the sound level. Graphite crucible efficiently discharges the current, resulting in lower noise level.

   Plasma reduces the sound level, because of plasma gas creates an easy path for the transfer of current through the cluster of electrons having increased conductance compared to the normal arc. But hydrogen plasma increases noise due to the burning of hydrogen gas with a hissing sound as compared to nitrogen plasma.
4. Hydrogen plasma erodes the magnesite crucible lining to a greater extent due to the reduction of lining material.

   Partitioning analysis of elements in metal, slag, and gas indicates the reduced magnesium exist in the slag and dust only.