1. Introduction

Sinter making is a very important intermittent step to produce pig iron from iron ore. During sinter making the green mix is charged onto a moving grate and ID fan is used to suck air through the green mix bed. The green mix constitutes a moistened mixture of iron ore fines, crushed flux and fuel (anthracite coal). Sulfur content in anthracite coal is in the range of 0.4 to 0.6 wt%. The top layer of the bed is ignited by an ignition furnace situated at the sinter charging side. Due to the effect of suction and presence of coke particles in the mix, the flame at the top layer, moves vertically downward by combustion of coke particles in the green mix simultaneously the sinter bed moves horizontally towards the discharging side. The gaseous product of combustion, calcinations and reduction processes that take place during sintering is known as waste gas (WG). Waste gas on its way from sinter bed to the atmosphere, passes through the gas pipeline, electro-static precipitator (ESP) and chimney. Due to shortage of anthracite coal, steel industry looking for alternate fuel for sinter making. Raw petroleum coke (RPC) is easily available and have high calorific value, so may be a suitable fuel for sinter making. Draw back associated with RPC is high sulfur (2–3.5 wt%) content in it.

Carbon steel and low-alloy steels are usually the preferred materials for structures of main gas pipeline of any sinter plants for their excellent mechanical properties and low price. The corrosion of mild steel in wet gas and multiphase gas environment is responsible for frequent maintenance, lower life cycle and production loss. The corrosion loss of metals is undoubtedly influenced by the nature of the atmosphere in which they are exposed.

Erosion leads to mechanical degradation of engineering materials, while corrosion is an electro-chemical process that leads to loss of material. The impact of particles on the internal walls of flow components, such as pipes, fittings, valves and pumps results in (a) enhanced corrosion due to the continuous removal of protective corrosion products and (b) erosion of the base material, especially at parts projecting into the main flow. The erosion effect of solid particles in pipelines or agitated vessels cause the passive layer to break.

Beside this, electrochemical effect of wet multi-component gas on pipe line corrosion is also common. An early study of corrosion in steel by electro-chemical techniques was carried out by Rozenfeld and co-workers. Fishman and Crowe attempted to study the effect of relative humidity on corrosion rate using potential transients with some degree of success. The amount of water vapour in the atmosphere particularly its variation during wet and dry seasons, affects the corrosion rate in pipe lines. Chloride ion is one of the most important natural pollutants influencing corrosion, but its role may change depending on the climate. However could be deviations to this statement. More recent reports suggest that the emphasis is on a proper interpretation of the complex temperature–relative humidity relationship and role of pollutants. Carbon dioxide is a major problem in the oil and gas industry, including effect of temperature, or some other vari-
ables like dew point temperature.\textsuperscript{20,21} The mechanism and aggressiveness of SO\(_2\) corrosion have been reported in many literatures.\textsuperscript{7,22,23} Combustion, however, typically involves the emission of smoke particles and hydrocarbons along with SO\(_2\).\textsuperscript{24,25} Critical environmental parameters known to be the relative humidity (RH) and the concentrations and transport rates of gaseous pollutants. Till now, corrosion study in co-pollutants environments restricted to laboratory only.\textsuperscript{26,27} It is generally assumed that the conjoint action of electrochemical corrosion and physical interactions produce far more damage than if each acted separately.\textsuperscript{28–31} Spalling of scales has been observed during the isothermal erosion-oxidation attack of several metals.\textsuperscript{32,33} The objective of present paper is to find out comparative erosion and chemical corrosion effect at different locations and positions on the main gas pipe line when raw petroleum coke (RPC) used as trimming fuel.

2. Experimental Procedure

Steel coupons (of 15 cm \(\times\) 10 cm \(\times\) 0.68 cm) were used for corrosion experiment. The composition of the steel coupons was determined using an optical emission spectrometer according to ASTM E 415-99a standards\textsuperscript{34} and is given in Table 1. The composition of RPC was determined using chemical analysis as given in Table 2.

The schematic diagram of a conventional Sinter Plant and the relevant locations are showing in Fig. 1 and Fig. 2 respectively.

The coupons were exposed at different wind boxes inside the main gas pipe line as mentioned in Table 3.

During the experiments, moisture content, temperature and velocity of the waste gas were monitored at different locations in the main gas pipe line. To ascertain the extent of erosion and electrochemical corrosion, some of the coupons were also placed at the center of pipe line normal to the gas flow direction, while others were placed close to the pipe wall. After exposure for 120 d, all the coupons were removed. The reaction product, either rust or a combination of rust and sintering by-product, were collected from the coupon surface for characterization. The coupons were subsequently measured for weight loss.

In order to evaluate the rust morphology, the reaction products were examined under a SEM JEOL JXA 6400 scanning electron microscope. An Energy Dispersive Spectroscopy (EDS. KEVEX Super dry detector) was used for determining the chemical composition of the powder. The structure of the powder samples was determined using an X-ray Philips diffractometer.

3. Results and Discussion

3.1. Environmental Variation within the Gas Pipeline

The velocity of the waste gas in the main gas pipe line varied from one location to another due to variation of waste gas volume. It was maximum at center near WB15

| Location | Position | Corrosion rate (mpy) |
|----------|----------|----------------------|
| Near wind box 15 | Center | 2.692 |
| Near wind box 15 | Wall | 2.742 |
| Near wind box 8 | Center | 0.722 |
| Near wind box 8 | Wall | 0.741 |
| Near wind box 1 | Center | 0.425 |
| Near wind box 1 | Wall | 0.441 |

Table 1. Basic composition of steel in wt%.

| C    | Si  | Mn | P  | Cu | Al   | Fe  |
|------|-----|----|----|----|------|-----|
| 0.13 | 0.015 | 0.87 | 0.017 | 0.035 | 0.042 | ~98.89 |

Table 2. Composition of raw petroleum coke in wt%.

| C     | S     | Ash | Volatile matter |
|-------|-------|-----|-----------------|
| 95.21 | 3.56  | 0.60 | 4.19            |

Fig. 1. Schematic view of conventional sinter plant: (a) charging, (b) sinter bed, (c) wind box, (d) main gas pipe line, (e) ESP, (f) waste fan and (g) chimney.

Fig. 2. Front view of sinter bed, wind box and main gas pipe line of sinter plant 1.
where as it was minimum on the wall near WB1 as shown in Fig. 3.

The moisture content in the carrier gas was approximately 22 g/m³ near WB15 as this wind box sucks air from the green mix (freshly charged onto the sintering bed). Moisture content in the sinter mix expected to be high near WB15 but gradually reduces as it approaches WB1. The carrier gas temperature near WB15 was low as it passes through the cold sinter bed that contains around 7 wt% moisture as shown in Fig. 4.

The moisture and temperature of the carrier gas experience opposite effects—while the moisture content decreased the temperature increased from WB15 to WB1 (see Fig. 4).

3.2. Surface Appearance of Corrosion Coupon

Surface appearances of the coupons before and after exposure to sintering conditions are shown in Figs. 5 and 6. It is evident that the coupon exposed near WB15 was severely rusted, whereas the coupon exposed near WB1 was rusted marginally. These phenomena can be attributed to the favorable conditions for electro chemical reactions near WB15 which as indicated earlier has a moisture content of 22 g/m³ in the waste gas at temperature of 43°C.

3.3. Electrochemical and Erosion Corrosion

The data of the overall corrosion rate of coupons exposed at different locations in the main gas pipe line is given in Table 3. The conditions of the pipe line are such that the exposed coupons experienced two types of corrosion namely (i) erosion and (ii) electrochemical. As apparent from the rusted surface appearance the corrosion rate was highest in the coupon exposed near WB15, while it was lowest near WB1. The corrosion rate of the coupon exposed near WB8, which is an intermediate zone, was found to be similar to the coupon at WB1.

The electrochemical corrosion effect on coupons surface exposed near wall at WB15 was maximum as compared to exposed near wall of WB1. This could be attributed to high humidity and low temperature (see Fig. 4) condition at WB15 as compared to the dry condition with high temperature at WB1. The phenomena near the wall of WB8 are identical to that of WB1, and this could be well explained by the significant change of slopes of the temperature and moisture in Fig. 4.

In the sinter plant gas pipeline situation, the carrier gas velocity was high along the center of the pipe and was negligible along the walls[35] as shown in Fig. 3(a). The design of the gas pipe line in relation with the sinter bed is such that the waste gas velocity was lowest at WB1 and was highest at WB15 as shown in Fig. 3(b). Therefore, the effect of particle impact on the coupon surface was of a low order at WB1 kept at the center of the pipe and there was no erosion effect at the wall of WB1. Contrarily, due to additive conditions, the cumulative gas velocity corresponding to the pallet entry location (i.e. WB15) was much higher than the pallet discharge location (i.e. WB1). As a
consequence, the coupon exposed at the center of WB15 experienced maximum erosion effect. The shining surface of the coupon due to continuous impact of carrier gas particles confirmed the effect of erosion. The volume fraction of particles however could not be determined quantitatively. Some effect of erosion was observed on coupons placed on WB8 as this location experiences an intermediate gas velocity (see Fig. 3(b)).

The overall effect of erosion and electrochemical corrosion on the coupons along a given section of the pipe line was same. While weight loss due to erosion effect was predominant at center, similar weight loss due to electrochemical reaction was obtained at the wall. This explains why two different corrosion mechanisms were active simultaneously under identical humidity and temperature conditions. However, the degradation of metal at the center was mainly controlled by the velocity of the carrier gas. Although the prevailing humidity and temperature conditions were responsible for electrochemical reaction uniformly along a given cross-section, the higher carrier gas velocity at the center contributed to erosion corrosion over electrochemical corrosion.

3.4. Characterization of Reaction Product

The reaction products on the coupon surfaces, exposed at different locations of the pipeline were characterized by SEM, EDS and XRD techniques. The morphology of the reaction products and the elements present in it are shown in Figs. 7–9.

The size of the reaction products formed on the coupon surface exposed near WB15 were bigger. The favorable environmental conditions were responsible for these bigger size particles near WB15. The amount of different elements in the reaction products varied for coupons placed at different locations in the main gas pipeline. Maximum amount of iron was detected in the reaction product on coupon placed near WB15 where as minimum amount of iron was detected in the reaction products on the coupon placed near WB1. This happened during electrochemical reactions of iron, wherein most of the Fe got converted to low temperature iron oxide. On the other hand, maximum amount of calcium, magnesium, oxygen, sulphur and chlorine were detected in the reaction products on the coupon placed near WB1. Flux materials such as limestone and pyroxenite, used for sinter making, were partially calcined/dissociated...
into lime and magnesia powders at high temperatures. These powders, fine and light in nature, normally were blown away by the waste gas but a portion of it gets deposited on the coupon surface. Maximum amount of these powders detected on the coupon surface exposed near WB1. Aggressive pollutant gases like SO₂ and Cl₂ were generated near the discharging end at high temperature, which subsequently gets absorbed by the sorbents (lime and magnesia) present on the coupon surface. This is evident from the EDS composition given in Table 4.

The reaction products collected from the coupon surfaces were analyzed by XRD techniques and the compounds present are indicated in Fig. 10.

Goethite and hematite was detected in the reaction products which formed on the corrosion coupon exposed near WB15 where as only hematite was detected in the reaction products which formed on the coupon placed near WB8. Magnetite also detected on the reaction product formed on the coupon surface exposed near WB1. This is primarily due to the high temperature of the carrier gas that promotes formation of magnetite. In addition to hematite and magnetite, other compounds such as manganese sulfate, gorgeyite, niningerite, potassium chloride, bronite and diopside were also detected. Aggressive gases, such as carbon dioxide, sulfur dioxide and chlorine were released from the sinter mix at very high temperature which subsequently gets adsorbed by the sorbents (lime and magnesia powders) present on the coupon surface and formed gorgeyite, niningerite, potassium chloride, bronite and diopside on reaction.

4. Conclusions

(1) The low temperature-high moisture at the charging side and high temperature-low moisture at the discharging side exist in the main gas pipeline. The waste gas velocity is maximum near charging side and minimum near discharging side. Aggressive environmental conditions near charging side resulted in faster corrosion. Low temperature-high moisture promotes electrochemical corrosion. However, the additional effect of waste gas velocity supersedes the electrochemical (EC) and promotes erosion corrosion effect at the center of the pipe line. Overall, the center experiences erosion corrosion where as the wall experienced electrochemical (EC) corrosion.

(2) Higher moisture content at relatively low temperatures promotes electrochemical reaction with formation of bigger goethite and hematite. Contrarily, at high temperature the fine sinter effluents like calsia and magnesia deposited on the metal surface. Also, aggressive gases like SO₂, CO₂ and Cl₂ released at high temperature near discharging end and passed through main gas pipe line which...
subsequently gets absorbed by the sorbents (lime and magnesia) present on the coupon surface and formed gorgeyite, niningerite, potassium chloride, bronite and diopside on reaction. The invariant conditions are responsible for formation of different reaction products along the sinter main gas pipeline.

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