CFD STUDY ON THE PERFORMANCE OF OXYGEN LANCE OF PARTIAL COMBUSTION UNIT AT DIRECT REDUCTION PLANT

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ABSTRACT

Direct Reduction Plant (DRP) is one of the most important components in iron and steel making process. The performance of the DRP is very much dependent upon the heat generation by the partial oxidation process to remove oxides inside the iron ore; which the process takes place at the Partial Combustion Unit (PCU). This unit is located between the process gas heater and the oxides removal reactor. The unit consist of a transfer line, and two oxygen lances with nozzle attached to each of the lances. Turbulence flow can help the unit achieve higher operating temperature. Of course the performance of the PCU can be assessed experimentally but that require expensive experimental setup. Alternatively, the same study can be performed via Computational Fluid Dynamics (CFD) at lower cost. This study aims to increase the performance of the PCU by evaluating the various designs by mean CFD. Two different lances design were evaluated in this work along with variation in operation configuration. The modelling of turbulence flow were realised via k-e model whereas the combustion process were modelled using the species transport with eddy-dissipation model. Predictions from CFD model were found to be in good agreement about 10% difference to the experimental data obtained from experimental work. This study also reveal an improvement opportunity of the PCU design as much higher temperature are achievable when wings attached to the lances to induce turbulence flow. This modelling exercise has demonstrated a cost effective route of design optimisation for PCU and hence should be used as tool for troubleshooting a design in future.

ABSTRAK

Direct Reduction Plant merupakan salah satu komponen penting dalam proses penghasilan besi dan keluli. Prestasi DRP ini adalah sangat dipengaruhi oleh penjanaan haba oleh proses pengoksidaan separa untuk menyingkirkan oksida dalam bijih besi dan proses ini berlaku di Unit Pembakaran Separa (Partial Combustion Unit). Unit ini terletak di antara pemanas proses gas dan reaktor penyingkiran oksida Unit Pembakaran Separa ini terdiri daripada 'transfer line' dan dua 'oxygen lance' yang setiap satunya mempunyai 'nozzle'. Pergolakan aliran yang tinggi dapat membantu unit ini untuk memberikan prestasi yang baik. Kajian ini melihat kepada reka bentuk 'oxygen lance' dalam memberikan peningkatan kepada prestasi unit tersebut dengan cara meningkatkan arus pergolakan di dalam system. Reka bentuk yang telah diubahsuai kemudiannya disimulasikan dengan menggunakan alat bantuan pengkomputeran iaitu 'Computational Fluid Dynamic' (CFD). Simulasi ini dijalankan dengan cara mentaksir konfigurasi 'lance' yang lebih bagus dengan menilai prestasi yang paling cemerlang yang mampu membantu meningkatkan kecekapan penghasilan haba oleh proses pembakaran. Keputusan yang diperolehi daripada simulasi tersebut membuktikan bahawa 'lance' yang dilengkapi dengan sayap (wings) dapat membantu meningkatkan keberkesanan penghasilan haba. Simulasi menunjukkan terdapat sebanyak 10.10% ralat namun diterima sebagai sesuatu yang memuaskan.

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LIST OF ABBREVIATION

DR	Direct Reduction
PO	Partial Oxidation
PC	Partial Combustion
DRI	Direct Reduced Iron
HDRI	Hot Direct Reduced Iron
HBI	Hot Briquetted Iron
CFD	Computational Fluid Dynamics
NG	Natural Gas
COG	Coke Oven Gas
EAF	Electric Arc Furnace
LES	Large Eddy Simulation
K.E	Kinetic Energy
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
O_2	Oxygen
H_2	Hydrogen
H_2O	Water Vapor
N_2	Nitrogen

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

In steel and iron making industries, natural gas plays important role as the main utilities for the plant. Apart from that, coal also being used in certain technologies of the industries. In Malaysia, local company produced both iron and steel and the raw materials which is iron ores normally imported. The process started with the production of iron by reducing the oxides inside the iron ores and the furthered to the steel making production as the final product. The steel is then distributed in various types such as billets (Perwaja Holding Berhad, 2009). The plant optimization should be performed in order to be profitable. The plant is consists of three main part which are Direct Reduction Plant (DRP), Direct Reduced Iron (DRI) Shed, and Steel Melting Shop (SMS). This study only focuses on the first component of the plant which is DRP.

In the part of iron making process, DRP is the most important plant. In this plant, natural gas firstly reformed into hot reducing gas also known as syngas which consist of carbon monoxide and hydrogen. The presence of these gases helps the reduction process of oxides inside the iron ore in the production of Direct Reduced Iron (DRI). This DRP can be designed to produce cold discharge DRI for direct feeding to an adjacent electric furnace meltshop. High composition of carbon DRI delivered to the meltshop by the hot direct feeding brought advantages to the system in terms of thermal energy from the reduction furnace as well as the unique high carbon content of the DRI hence improved the quality and economically effectives (Tenova et al.). Generally, there are two route of steel making process, via Blast Furnace and via Direct Reduction Plant.

In the DRP, there are several units play important role in the production of DRI and one of the most important units is Partial Combustion Unit (PCU). This PCU is located between the process gas heater and the oxides removal reactor. The unit is build up with a transfer line, and two ȍxygen lances with nozzle attached to each of the lance. The transfer line is used to transfer the process gas from gas heater to the reactor while the oxygen lances are used to supply the oxygen to the unit. The oxygen is supplied with the purpose of to favour the oxidation process to take place in order to increase the operating temperature. Higher operating temperature gives better performance to the unit.

1.2 Direct Reduction Plant

Partial combustion unit is the unit where the process gases consist of high concentration of hydrogen and carbon monoxide is partially reacted with the oxygen that supplied through the oxygen lances. The process gases that come from the natural gas is firstly reformed into hydrogen, carbon monoxide, carbon dioxide, methane, nitrogen and a little amount of water vapour. In the DRP, the gases is reformed into single component of gases through gas reformer and then supplied to the gas heater to increase the temperature. Insufficient of heating value caused the PC concept to be applied in this unit and thus help the plant to achieve the acquired temperature of process gases. From the basic concept of chemical reaction, combustion also can be classified as chemical reaction. The reaction that occurred between the process gases and the oxygen reaction in the PCU is believed to produce heat and called as heat of combustion. The heat that was produced is then used by the unit to increase the temperature of the process gases and hence reduced the energy consumption for the process gases to achieve the required temperature. In Chapter 2, the details concept on the partial oxidation or partial combustion and the technologies of direct reduction process is explained more detail.

1.3 Problem Statement

The simple and basic design of Oxygen lances installed in the transfer line at PO unit seem can be improved in order to give better performance for the unit hence beneficial to the company. By performing CFD simulation study, the unit performance can be investigated and new design is proposed for the unit optimization. The performance of both simulated result between current design of lances and the proposed design of lances can be compared and some validation using real plant data taken from Perwaja Steel's PO unit was performed. Besides, the amount of oxygen supplied to the unit can be investigated either the oxygen/fuel ratio can resulted in optimum performance by evaluating the temperature profile of the unit.

1.4 Objectives of Study

The objectives of this study are:

1.4.1 To evaluate the performance of the partial combustion unit with current installation of oxygen lances by analyzing the profile of the temperature using CFD.

1.4.2 To propose a new design configuration of oxygen lances for the purpose of enhancing the performance of the PCU.

1.5 Scopes of Study

To achieve these objectives, the scopes of this study have been identified as follows:

1.5.1 Performing simulation on partial combustion reaction in partial combustion unit in order to identify the heat generated by the unit with current installation of oxygen lances.

1.5.2 To propose new design modification for troubleshooting of the problem in the partial combustion unit by using CFD simulation and comparing the heat generation of both configuration of oxygen lances.

CHAPTER 2

LITERATURE REVIEW

2.1 Direct Reduction Plant

In steel making industries, the names of HYL, Tenova, Midrex and etc. is common for the involved industries. Generally, all the technologies applied the same of concept towards same goals for the operating plants. Such kinds of technologies were being created and upgraded towards lowering the operating cost and maximizing the productivity and make the plant profitable for the companies. Usually, Natural Gas is used as the utilities at the plant especially Direct Reduction Plant. Reformation of NG into high concentration of reducing gases such as Hydrogen and Carbon Monoxide is applied at the DR plants.

There are several process and routes of making iron. **Table 2.1** shows the typical process and routes of iron making and the details of the process. Generally, there are two routes of iron making process which are smelting reduction and direct reduction. For smelting reduction, the process used either coke or coal as the sources of the reducing gases while for direct reduction, the sources that can be used either Natural gas or coal as well. Furthering this chapter, author only focus on the direct reduction process since the focus of this research only related to this direct reduction route of iron making process.

DR process is specifically designed for converting the iron ore either pellet or lump into metallic iron by using reducing agents. Through the process, Oxides is removed from the iron ore chemically based on H_2 and CO for the production of highly metalized DRI (Danieli & Tenova et al.). In addition, generation process of reducing gases can be through the routes of direct by in-situ reforming of natural gas either inside the shaft furnace or steam reforming, gasification of fossil fuels, biomass, etc. as syngas or from Coke Oven Gas (COG) sources (Danieli et al.). Besides, the hot reducing gases also can be generated using separated reformation process and partial oxidation process (Dash et al., 2009.).

Figure 2.1 shows the typical process of Direct Reduction plant. The PO unit is located between the gas heater and the reactor. The combustion chamber is consisting of transfer line and two oxygen lances. Inside the combustion chamber, the reducing gas is fed into the reactor which the reduction of iron ore occurred through a transfer line. The dimension of the transfer line is about 0.633 m of radius and 6.35 m of length. At local plant, the injection of oxygen through the lances is occurred at the position 1.35 m from the inlet of the combustion chamber. In the combustion chamber, there were partial combustion process took place between all the process gases that passed through the transfer line and the oxygen introduced.

The partial combustion process is believed can boost the temperature of reducing gases before entering the reactor for the reduction process. Besides that, partial combustion also makes it possible to overcome the heaters' constraints for achieving reduction temperature above 900^0C (Raul et al., 1995.). Furthermore, higher temperature need to be increased caused in higher operating cost since the power need to heat up the process gases is also increased. Therefore, the partial combustion unit is really important to be optimized for the advantage of the company.

The used of oxygen in a direct reduction plant can significantly increase the productivity by meaning accurate optimum air fuel ratio need to be applied for the partial combustion process. Hence, reducing gas heating process and also the proper used of energy, an overall optimized process scheme can be achieved in terms of both plant productivity and energy consumption (Raul et al., 1995).

Table 2.1: Typical process and routes of iron making (Dash et al., 2009)

Process	Smelting Reduction		Direct Reduction	
Reducing Agent / Ore Charge	Coke	Coal	Natural Gas	Coal
Lump Ore/ Sinter/ Pellets	Blast Furnace, Submerged EAF	Corex	Midrex, HYL, Midrex OXY+AREX	Rotary Kiln
Ore Fines	Star Furnace	Romelt, Primus, Hismelt, Dios, Ausmelt	Fior, Finmet Circored, Iron Carbide	Circofer, Comet, HI-QIP
Ore-Coal Pellets/ Briquettes		Fastmelt, Tecnored		Dry Iron, Fastmelt, Inmetco, Itmk3

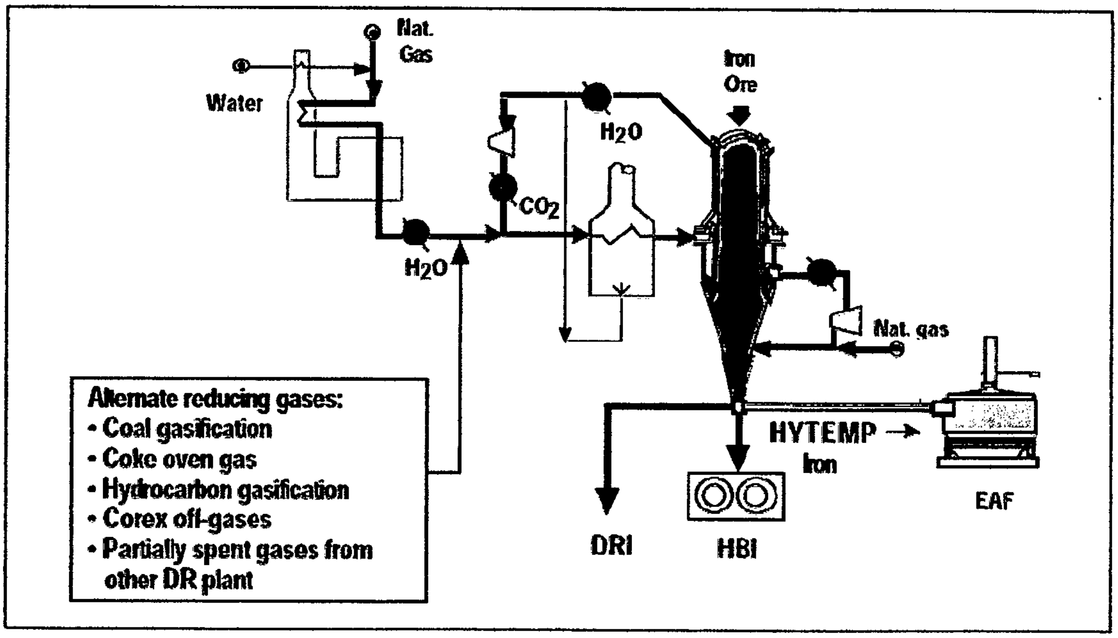

Figure 2.1: Process flow diagram of iron making process (Raul et al., 1995)

2.2 Direct Reduction Technologies

According to Raul and Matthias (2002), the evolution of DR technologies to the current situation involved hundreds of different DR process concepts either laboratory scales or pilot scales levels. Most were obtained to be technically or economically unfeasible and thus abandoned. Nevertheless, some other were successfully improved and commercialized into full-scale operation. However, some of those which reached the industrial scale level could not fully achieve the technical and economical parameters and at last being abandoned. Several cases have been experienced where some of the developments come into failure and disappeared at an advanced stage and the worst part is when it occurred after a long time significant capital expenses and effort as well. The results are not only costly inefficient for the developer, but also affected some other investors and customers as well.

As mentioned, new DR processes developed need a long time and significant capital cost. An investor who wills to develop the technologies must also consider the real potential of competencies in market mainly if other technologies already existed and commercially proven. In this kind of situation, significant economic advantages such as lower energy consumption and investment cost with higher product value or higher flexibility for using cheaper raw materials and reducing gases must be guaranteed by a new DR technology. At the beginning of the new era, the DR technologies with gas based-processes lead the world in the related fields of industries. With the operation under a moving bed reactor (shaft furnace) concept of iron ore reduction, HYL and Midrex technologies use either iron pellets or lump ores as the raw materials. Impressively, both of the technologies have already proven extensively in economic results and plant reliability up to higher than 90% of plant availability.

With completely developed and highly flexible of process steps, industrial plants which based on these two technologies can provide up to 90% of the world production of DRI and HBI. This is because these two technologies offered minimum risk to the investor, unlike the case when new commercially unproven technologies are used. Some new or advance improvement of DR processes have come recently into the market, with the advantages on the DRI and HBI production costs and better quality of products claimed. However, some of the industrial plants that do not fulfil the expectation and the process performance requirements have yet to be demonstrated on a continuous basis. These technologies-based projects have exceeded by far the capital costs, implementation time-schedule, start-up curves and expected operating costs. Preceding this chapter, some details on the DR technologies will be discussed

2.2.1 HYL Direct Reduction Process (Raul et al., 2002)

The first technology that successfully operated at industrial scale in the world was HYL in 1957 with a technological concept proposed that was a real solution to the metallic needs of Hylsa in Mexico. With the fixed bed reactor-based concept, it was resulted to achieve the requirement with this attractive and innovative technology that other steelmaking companies acquired the HYL process licence. For a total capacity of over 9 million ton/year of DRI, approximate of 22 DRI units were installed in different countries. However, due to its batch nature, it was foreseen by HYL that the competitiveness of this technology would be limited. Therefore, a research program was started in 1967 with the purpose of to develop a continuous processes (moving bed), starting the first industrial plant in May 1980 in Hylsa Monterrey, Mexico and led to higher plant productivity, superior DRI quality, lower energy consumption and a simple plant operation.

Some improvements have been incorporated in the HYL moving bed process through the years **Figure 2.2.1** shows the HYL process development. A CO_2 removal system was implemented in the reducing gas circuit in 1986 and thus allowing significant improvements in productivity, energy consumption and DRI quality as well. The gas reformation process was also decreased in the industrial operation by about 50% and the reactor productivity was increased by a similar figure. Then, the partial combustion technique was applied in HYL industrial plants in 1995 by injecting the oxygen at the transfer line between the reducing gas heater and the reactor. This scheme allowed an important increase in the reducing gas temperature, as well in-situ reforming, decreasing the consumption of the reformed gay by about 25%, with the combination of increased in reactor productivity. Next, the total natural gas feed and oxygen injection to the reduction reactor in 1998 led to the "HYL Self-Reforming scheme", where the make-up of reformed gas is decreased to zero. This scheme is in successful industrial operation in the Hylsa 4M plant since April 1998 and then in Hylsa 3M5 plant since July 2001.

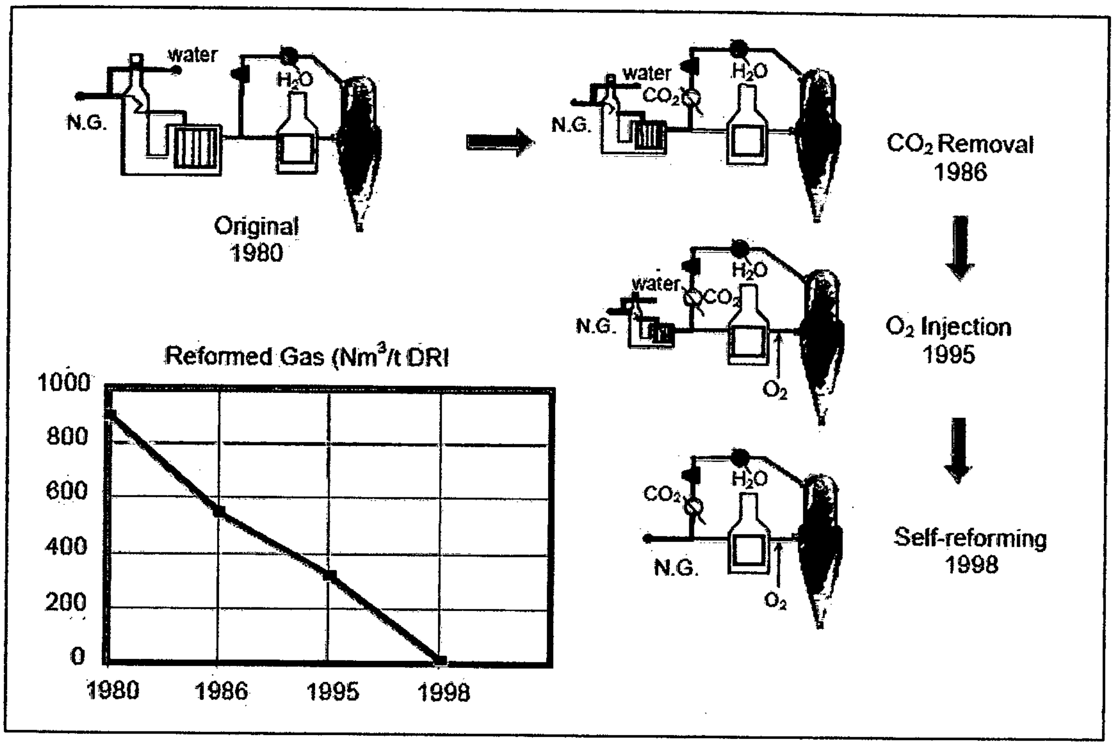

Figure 2.2.1: Development of HYL technology (Morales et al., 2002)

Figure 2.2.2 presented the general process of HYL technology. By the used of reducing gases in a solid-gas moving bed reactor, the HYL process is designed for the conversion of iron ore (pellet/lump) into metallic iron. For the production of highly metalized DRI/HBI, oxygen is removed from the iron ore by chemical reactions based in Hydrogen and carbon monoxide. Depending on the specific requirements of each user, the technology offered the flexibility to produce three different product forms. In the reduction reactor, the reducing gases are generated by self-reforming. Then, the NG is fed as make-up to the reducing gas circuit and oxygen is injected at the reactor inlet. Reducing gases was generated in-situ (H_2 and CO) by the partial oxidation process with the increased of operating temperature which is required for reforming and iron ore reduction process. Once in contact with the solid materials inside the reactor due to the catalytic effect of metallic iron, further reforming and cracking are carried out. Reformed gas and coal gas can be used as other alternative sources of reducing gases in HYL plants under same basic process scheme.

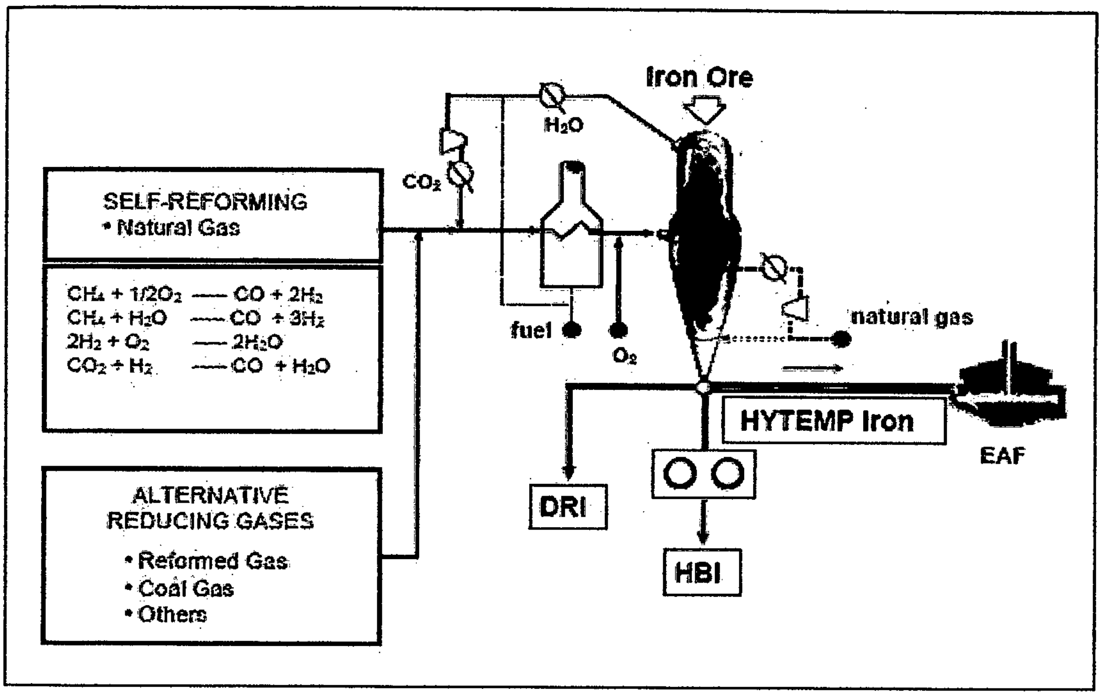

Figure 2.2.2: General process of HYL technology (Morales et al., 2002)

2.2.2 Midrex Direct Reduction Technology

During the 1960s, the Midland-Ross Corporation was developed the Midrex Process which had pioneered shaft furnace technology and stoichiometric reforming for use in processing minerals. The first Midrex Plant was built in Portland, Oregon, USA in 1969. Then, about 49 additional modules have been sold in 18 countries since then. Many technical improvements have been developed including larger size of shaft furnace, in-situ reforming, greater heat recovery, improved catalysts and hot briquetting during the quarter century since commercialization. Then, Midrex continues to advance the shaft furnace direct reduction technology in terms of state-of-the-art in the areas of raw materials flexibility, shaft furnace productivity, product characteristics, flow sheet options and energy efficiency (Winston et al.).

Midrex is a technology company based in Charlotte. Midrex reduction process is the dominant technology for making DRI and in 1998; approximately 67% of all DRI was produced using this technology. Inside a tall vertical reactor called the Midrex Shaft Furnace, the Midrex process performs the iron ore reduction activities. With the continuous fed of iron ore, the process was accomplished which is similar in size and shape to marbles, flows downward through the Shaft Furnace by gravity and counter-currently flow to the hot reducing gases which rise up through the shaft furnace. Then, the hot reducing gases reacted with the oxygen atoms in the iron ore (iron oxides) and stripped away the chemical bound of the oxygen (Cheeley et al., 1999).

The Midrex process consists of three major stages which are reduction process, reforming of gases and heat recovery. During the reduction process, iron ore either in pellet or lump forms is introduced through a proportioning hopper at the top of the shaft furnace. Descending through the furnace by gravity force, the ores heated and the oxygen is removed from the iron (reduced) by counter currently flowed gases which containing a high concentration of hydrogen and carbon monoxide. These gases therefore reacted with iron ores and converted into metallic iron, leaving water vapour and carbon dioxide. For the production of cold DRI, the reduced iron is cooled and carburized by counter-flowing cooling gases in the lower portion of the furnace. For this forms of product, methane is preferred for the endothermic carburization process. Besides that, DRI also can be discharged hot and fed to a briquetted machine for the producing HBI, or fed hot as HDRI directly to an Electric Arc Furnace (EAF). **Figure 2.2:3** shows the process flow diagram of Midrex technology reduction plant.

While during the reforming process, in order to maximize the efficiency of reforming, offgas from the shaft furnace is recycled and blended with fresh natural gases. This gases is then fed into the reformer, which a refractory-lined furnace containing alloy tubes filled with catalyst. Next, the gases are heated and reformed as it passed through the catalytic tubes and the newly reformed gas which containing 90 to 92% of hydrogen and carbon monoxide. Furthermore, the gases were fed into the shaft furnace as reducing agent for the reduction process. At the heat recovery part, the thermal efficiency of this Midrex reformer is greatly enhanced by the heat recovery system. The sensible heat generated from the process is recovered from the reformer flue gas to preheat the feed gas mixture, the burner combustion air and the natural gas feed. In addition, the gas may also be preheated depending on the economics effect though.

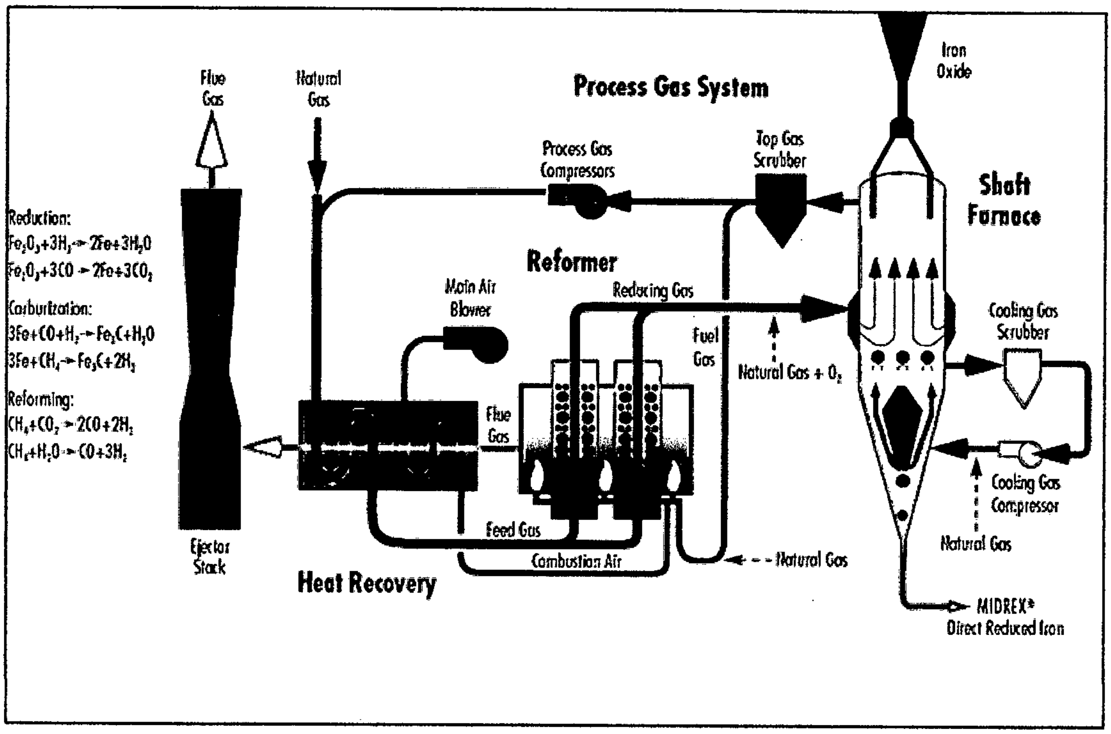

Figure 2.2.3: General process flow of Midrex Technology (Midrex technology plant manual.)

Other than HYL and Midrex, there are several technologies that used in the production of steelmaking industries. For every technologies, wide variety of furnaces being used including vertical shaft, multiple hearth, rotary kiln, rotary hearth, fluidized bed reactors and bath smelting vessels which resembled chemical reaction reactors, beside converting the steel and also acted as arc furnace style water cooled panel lined units illustrate relentless pursuit of appropriate new technologies to bring down capital and works costs in different contexts. Preceding this chapter, some brief description on the coal based hot metal process for the production of DRI is discussed.

2.2.3 Corex Process

This Corex process consisted of a melter gasifier where coal is gasified while injecting oxygen and pre-reduced the iron ore is melted. The produced gases are then used as reducing gas for the purpose of reduction process in an upstream shaft furnace. High pressure of coal gasification process suitably modified and dovetailed with gas based DRI has led to successful creation of this commercially viable new technology for molten iron. **Figure2.2.4** shows the process flow diagram of this Corex technology process.

2.2.4 Romelt Process

Reduction and melting processes are carried out in a single reactor in this process. During the reduction process, iron oxide is reduced as it passed through a foamy slag with the introduction of oxygen through two rows tuyers in the reactor. The side walls are line with water cooled panel by adoption of electric arc furnace technology for iron making process. Other than that, the reactor has the ability to process wide variety of materials including fines, ore slimes and plant wastes because of this process is easily to operate and environmentally friendly as demonstrated in a 300000 tonne per year unit at Novolipetsk in Russia. Intensively oxygen is the biggest advantage for this process while an efficient heat recovery from the flue gases is a vital economic requirement. **Figure 2.2.5** described schematically about the process.

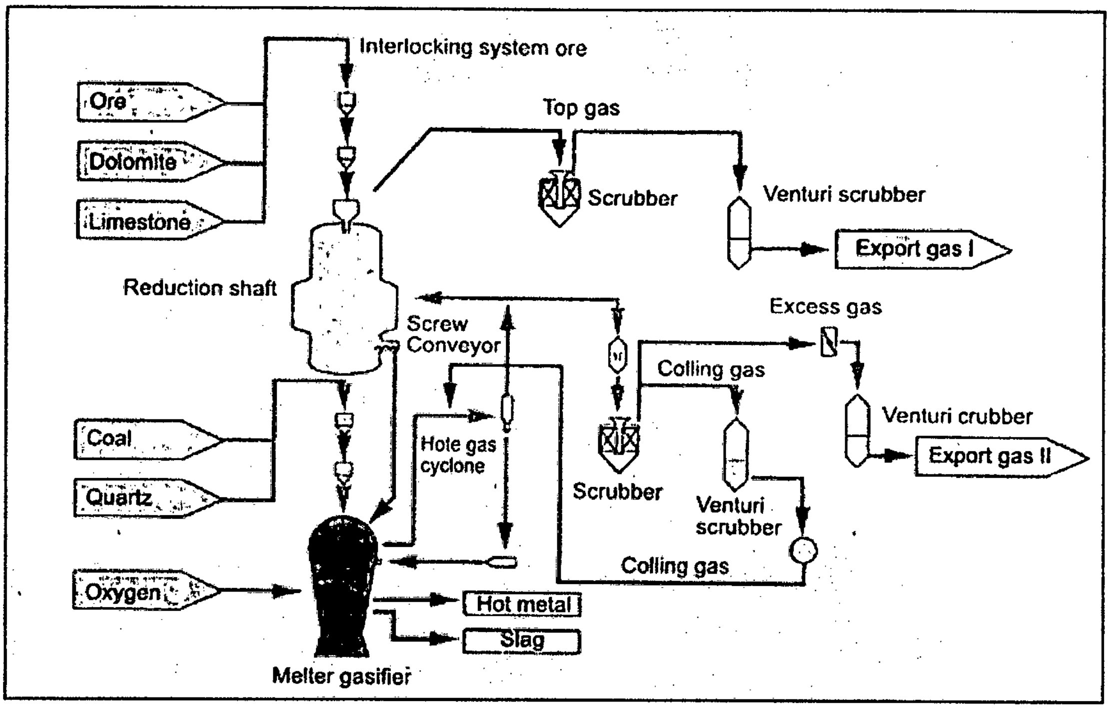

Figure 2.2.4: Corex process of DRI production (Dash et al., 2009)

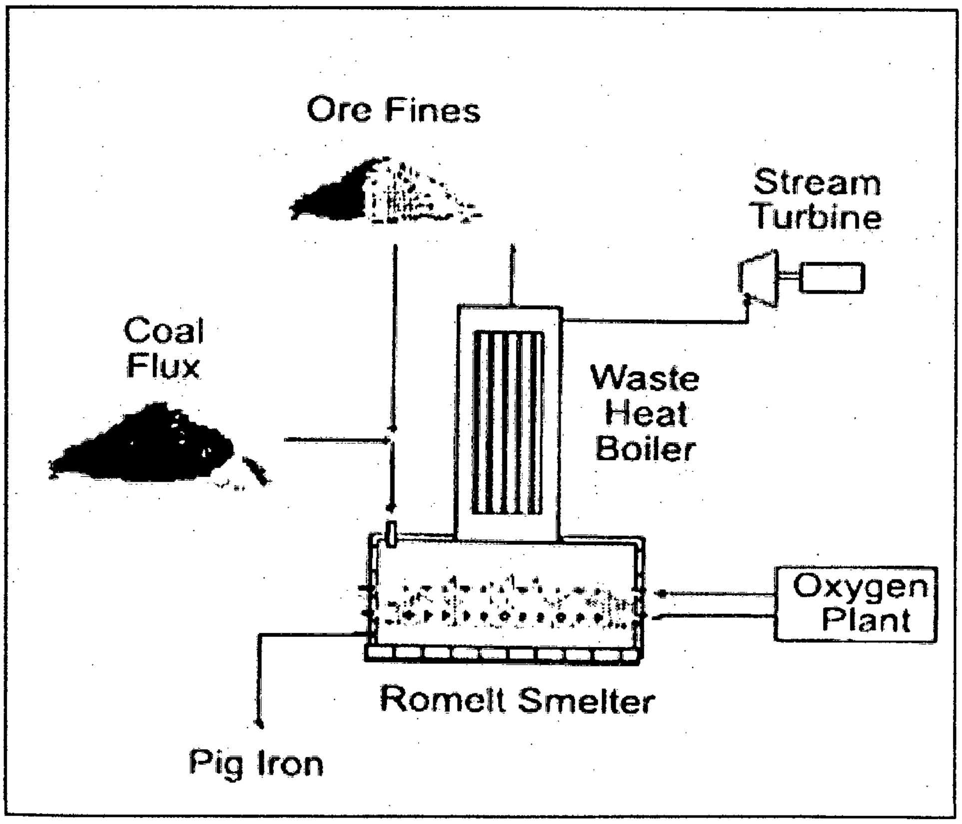

Figure 2.2.5: Flow sheet of Romelt process (Dash et al., 2009)