Smart design for man machine interface for EAF to improve efficiency

by

Pooriya Azadegan

Università
di Genova

Master of Science in
Energy Engineering

Advisor

Professor Agostino G.Bruzzone

Co Advisor

Professor Marco Gotelli

Dr. Kirill Sinelshchikov

July 2024

Table of Contents

Abstract

The electric arc furnace (EAF) is a key part of modern steelmaking. It can melt scrap metal into high-quality steel components. This thesis looks at ways to make EAFs more efficient.
It focuses on designing a better man-machine interface (MMI) and ways to help trainees learn about EAF operation. This should help them work faster and use less energy.

The thesis starts with a description of EAF operations, including its parts, safety measures, and on-site practices. Operators are important in this industry. Trainees will learn about safety, process control, and equipment maintenance to maintain furnace performance.

This is done by creating a BPMN diagram, which shows exactly what the operator has to do during each phase of the EAF operation. It is a model used to investigate how operators work in steelmaking.

This thesis contributes a virtual control panel for an electric arc furnace (EAF) with visualisation using Python and TKInter. This virtual panel helps operators learn faster. Operators can see important furnace details like temperature, power, current, and carbon via this interface. It helps operators monitor and control furnace conditions in real time to make high-quality steel while using less energy.

This thesis shows how smart MMI designs can help operators work well in EAF facilities. Research could look at making the virtual control panel better and using it with predictive maintenance.

Chapter 1:
Introduction

1. Introduction

Steel production has been a cornerstone of industrial development, shaping the modern world through continuous innovation and technological advancements. This chapter provides a foundational overview of steel production, tracing its historical evolution and highlighting the key milestones that have defined the industry.

We begin by exploring the essential principles and processes involved in steel production, setting the stage for a deeper understanding of its complexities. The historical journey of steelmaking is then charted, from ancient ironworking techniques to the sophisticated methods employed today. Notable developments include the introduction of the blast furnace in the 14th century, the creation of blister steel during the Industrial Revolution, the revolutionary Bessemer process of 1855, and advancements in hearth and electric steelmaking up to the late 20th century.

The chapter also delves into modern steelmaking technologies, examining the blast furnace, basic oxygen steelmaking (BOS), and the electric arc furnace (EAF) process. These technologies have not only enhanced production efficiency but also addressed environmental and economic challenges, making steel production more sustainable and cost-effective.

Furthermore, the differences between EAFs and other steelmaking processes are analyzed, with a focus on pricing advantages, environmental sustainability, and operational efficiencies. This introduction sets the framework for understanding the past, present, and future of steel production, preparing readers for a detailed exploration of the methodologies and innovations that drive this vital industry.

2. Foundations of Steel Production

Steelmaking has high importance across various aspects of modern society due to its versatility, durability, and economic impact. Steel serves as the backbone of infrastructure, enabling the construction of buildings, bridges, and roads worldwide. It plays an important role in transportation through its use in vehicles, aircraft, and ships, ensuring safety and efficiency in travel. In manufacturing, steel is essential for machinery, equipment, and tools, supporting industrial productivity and innovation.

It also supports energy infrastructure, including pipelines and renewable energy structures, contributing to energy security and sustainability. Moreover, steel enhances everyday life through consumer goods, appliances, and medical equipment by leveraging its strength, reliability and recyclability. The steel industry not only drives economic growth but also advances environmental sustainability through efficient production processes and extensive recycling efforts. Overall, steelmaking's enduring significance lies in its ability to meet diverse societal needs while fostering development, resilience, and progress globally.

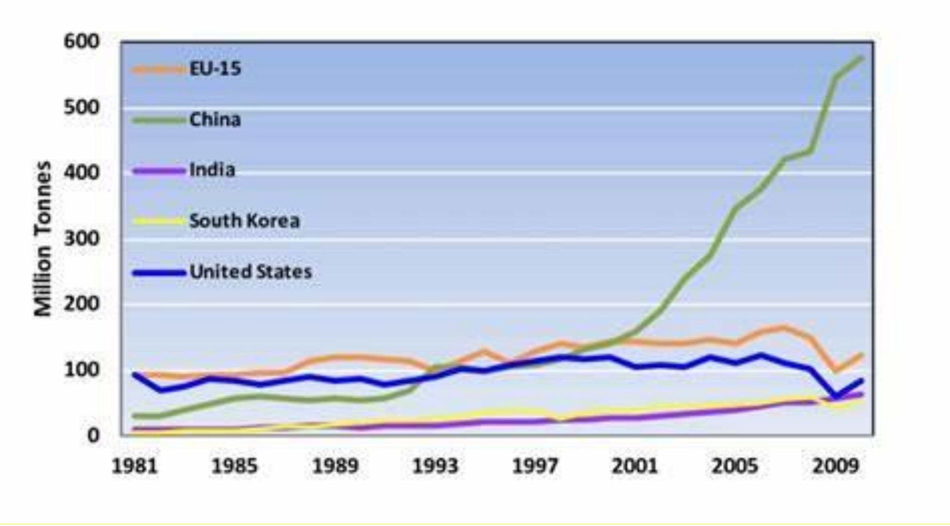


Figure1. Steel consumption in countries

Metal ores are first dug out of the ground, from the earth’s crust. All these ores are minerals, containing a large metal that can be extracted from the ore. Iron ore, for example, is a mineral rich in iron oxides (the most common element), and steel production depends on minerals with high-iron content. After being mined from the earth, they require mineral processing before attaining metal quality.

The first step of metallurgy is done by crushing and grinding the ore into a fine powder to extract metal from the crushed ore. There are different approaches used to concentrate the metal content of an ore, including magnetic separation, flotation, and chemical reactions.

Once the metal is extracted, it is melted or reduced. The third stage is reduction, wherein the concentrated ore is heated in a furnace with a reducing agent like coke, freeing the metal from its oxide. This is because iron ores are mainly reduced to oxidised form in a steelmaking furnace, which then produces hot metal or pig iron. The impurities sink to the bottom, where they get encased in a layer of slag and can be syphoned off.

The process of pouring molten metal into a mould to get desired shapes is known as casting, which comes next in metallurgy after forging. This process includes melting the metal, usually in a furnace, to make it liquid. After that, the molten metal is poured into a mould to give it the geometry of our final product.

Moulds are constructed from a few different materials (for example, sand or ceramics) and can also be used over and over again for multiple castings. As the metal cools, it solidifies within the mould and reflects that shape, taking every intricate design or pattern precisely.

When the metal has finally cooled, the mould is removed, and there are castings made out of metal. The casting may then "work in a green state" when it changes from the cast part to the final specs and characteristics. This might include being machined, heat-treated, or surface finished to add more mechanical strength or aesthetics.

The process can produce complicated and large-sized parts, such as collapsible bodies (expenditure moulds) that allow a single piece to be produced with integral fasteners or spring components, which could not be easily achievable via other methods. The extensiveness of this moulding technique allows it to have applications in several different industries, and metal casting is, therefore, one of the core processes used most commonly.

3. History of steelmaking

The history of steelmaking is a fascinating journey of innovation and technological advancement. From ancient ironworking techniques to the sophisticated processes of today, steel production has continually evolved to meet the growing demands of society.

Key milestones include the development of the blast furnace in the 14th century, the production of blister steel during the Industrial Revolution, the groundbreaking Bessemer process in the mid-19th century, and the advent of electric steelmaking and the basic oxygen process in the 20th century. Each of these advancements has contributed to making steel a fundamental material in modern industry and infrastructure.

3.1. The Evolution of Ironworking in Ancient Times

Ironworking history Ironworking has long held a special place in human technological advancement. It began around 2000 B.C. in Ancient Anatolia, marking the introduction of iron as a major material, replacing earlier metals like copper and bronze for utility purposes. The manufacture of iron spread throughout Southeast Asia by 1000 B.C. and into Eastern and Western Europe some two centuries later. Iron started to be more widely used by 500 B.C., but the spread of knowledge took longer; China did not learn about iron until around A.D.

Early iron production was limited, using bloomery furnaces to produce sponge iron that could be worked into wrought products. By 900 B.C., Egyptians had found means of heat-treating that made virgin steel suitable for tools and weapons. Between 206 B.C. and A.D. 25, China and Japan were using advancements in ironmaking to produce carbon cast iron, if not heat-treated steel itself.

From circa 500 BC to the 15th century, during the period of the Roman Empire, as a result of significant investment in metallurgy and ironmaking technology there was an increase in production throughout their territories. After the Roman Empire collapsed, iron production declined in Europe until around mediaeval times, when bloomery furnaces were water-powered and enabled higher temperature. This development allowed for the production of molten cast iron. The cast iron could then be re-melted into wrought iron, further solidifying the method of working with what was, at that time, a rare yet esteemed material.

3.2. The Blast Furnace (14th Century)

The blast furnace was invented in Europe during the 1300s, and it dramatically altered the nature of iron production. Because the blast furnace had a continuous supply of hot air to increase the temperature, it could produce liquid iron (or pig iron) instead of earlier furnaces that produced solid blooms. It meant iron could be provided from a blast furnace in large quantities and either cast into moulds or wrought iron. The greater efficiency led to the extraction of larger tonnages of iron ore and coal, which in turn increased both production capacity and scale-key factors behind the development that helped make steel one of the most important materials for modern industrial society.

3.3. Blister Steel and the Industrial Revolution (18th Century)

The 18th century saw significant advancements in steel production. Early in the century, carburization was commonly used to convert wrought iron into blister steel. These wrought iron pots were locally known as Sachihommel in Old German, but later the term was replaced with Eisenhut, meaning Iron hat. This process was patented but shared among armour manufacturing houses in Europe, using Swedish wrought iron to make very pure steel. The introduction of coke-fired blast furnaces to replace those using charcoal created cheaper cast iron, prompting the Industrial Revolution.

3.4 Bessemer Process (1855)

The biggest step made in steelmaking arrived in 1855, when Henry Bessemer invented the pneumatic steelmaking process, later named the Bessemer process. It worked by blowing air through the molten pig iron so as to eliminate impurities without the waste of time and expense of doing it in open hearths. The addition of phosphoric ores to the charge base was demonstrated by Thomas and Gilchrist in 1878, who thereby achieved a more general solution for the utilisation of iron ore with high amounts of potentially harmful phosphorus -bearing minerals using some fundamental Bessemer process improvements.

3.5. Hearth Process

Open-hearth furnaces were developed in the 1860s, pioneered by Pierre-Émile Martin. This method in steel manufacturing involved a comprehensive approach, where molten pig iron and scrap were melted together in a furnace. Open-hearth furnaces were known for their oxidising process, which requiring higher temperatures compared to general smelting furnaces, which were used for refining or melting charges. The design's flexibility allowed adaptation to a wide range of molten pig iron and scrap, making it the most widely used steelmaking method until around 1980.

3.6. Electric Steelmaking (1870s - 1989)

The electric arc furnace was developed in the late nineteenth century, but it took a long time to surpass the Bessemer and open hearth processes. It was originally patented by Sir William Siemens in the late 1800s. Small electric-arc furnaces, suitable for melting approximately one tonne of steel and used primarily in the production of tool steels, were introduced by 1900.

During the following decades, those furnaces greatly increased in capacity and efficiency. The electric-arc furnace was a regional and temporary offshoot of the scrap-and-pig iron arms race, but by 1950 it enabled top-quality steel to be made from no more than scrap. By 1989, electric-arc furnaces had become a significant segment of the worldwide steel industry, nearly accounting for more than a quarter of its production.

3.7. Basic Oxygen Process (1949)

This post-war period also saw the introduction of Austria's Linz-Donawitz process, in which oxygen was blown through a lance into a molten charge to make steel quickly. The basic oxygen process (BOP), as it is known, rapidly became predominant due to its lower cost and capability of producing large quantities of high-quality steel.

4. Modern technologies in steel making

Modern advancements in steelmaking have revolutionized traditional processes, enhancing efficiency, quality, and sustainability. This section examines the latest innovations in Basic Oxygen Steelmaking (BOS), Blast Furnace (BF) methods, and Electric Arc Furnace (EAF) operations. These technologies, including automation, artificial intelligence, and advanced sensors, improve production capabilities, reduce environmental impact, and meet global market demands.

4.1. Blast furnace

Iron ore is converted to molten iron within blast furnace-vertical shaft structures built with precision engineering that create a high-temperature zone for the transformation of raw material into liquid form. It is essential for the production of pig iron, a basic material in steel manufacture. Molten iron is collected at the bottom. At the top of the hearth is a bosh zone to facilitate heat exchange and ore reduction. Above the furnace, layers of limestone (flux), coke and iron ore are added before melting.

To be efficient, charges need to rely on a hearth suspended at the highest point of the heater by loading materials in alternating layers. This is achieved predominantly by reducing iron oxides into metallic iron using carbon monoxide created from coke. Limestone (from overburden or quarry waste) acts as a flux in the smelting process to separate impurities from molten iron.

Coke, produced from coal at the highest temperature through pyrolysis, not only reduces iron oxides but also provides the necessary temperature for the reaction between ore and flux. The environment within the furnace remains gas-permeable due to its porous construction, which in turn contributes to efficient performance.

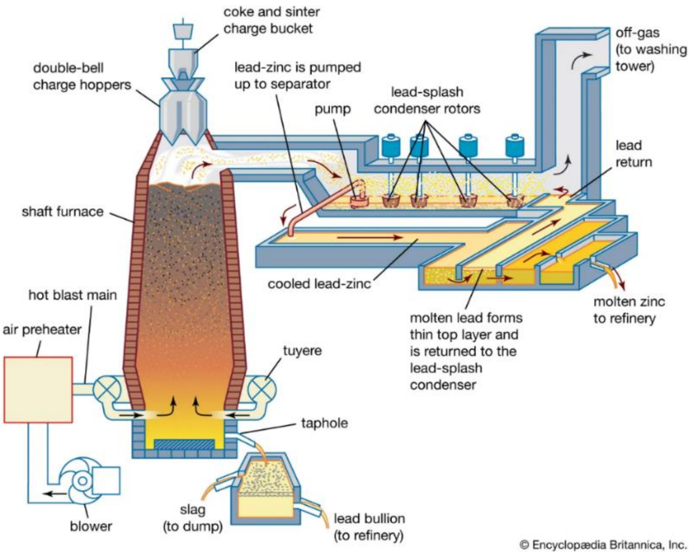


Figure 2. Blast furnace.

4.2. Basic oxygen steelmaking (BOS)

BOS is a mature and large scale process that produces vast quantities of molten metal in the worldwide steel producing industry, mainly for the basic grades of carbon steel. This is where molten pig iron and steel scrap are charged into a Basic Oxygen Furnace (BOF) vessel, which reacts with the oxygen being injected into it. Under a basic slag, this reaction proceeds, forming steel.

BOS is an essential process worldwide for steel production, covering around 60% of total world crude-steel output, and producing Steel over 1.4 billion tonnes on a yearly basis. The principle metallurgy material other than 70-80% liquid hot metal from blast furnaces is steel scrap (to adjust the initial input of processing).

Naturally, this reaction of preheated oxygen with carbon and silicon in the hot metal transforms all elements through an exothermic process within a BOF vessel, including specific iron traces as well as manganese and phosphorus.

The post-combustion of carbon monoxide creates a lot of heat, which, in addition to the low delta formed by these elements, results in molten steel with an elemental composition between 1600-1650 ℃ . The resulting steel can either be poured and used directly or further processed into slabs, billets or any other desired shapes, which are mostly cast from another process such as ingot casting or DC casting.

Furthermore, BOS typically uses vessel sizes of 250 tonnes and has a tap-to-tap cycle time of approximately 40 minutes (including a refining period of about 20 minutes). Operators at control pulpits located around the vessel watch and adjust process variables to produce quality steel efficiently.

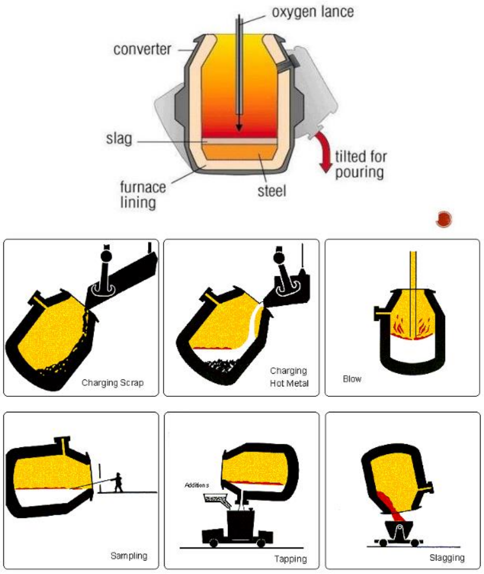


Figure 3. BOS.

4.3. Electric arc furnace (EAF)

The Electric Arc Furnace (EAF) process is a vital component of modern steel production, highly regarded for its economic efficiency in recycling cold scrap metal. The EAF was first made for the generation of high-quality steels. those used in machines and spring steel, which requires accurate control over composition, but now produces almost all grades, including alloy, stainless and other special carbon or low-alloy steels.

The EAF has a circular bath with a movable roof and three graphite electrodes that can be raised or lowered vertically. The furnace is charged with scrap metal using large steel baskets that are lowered into the furnace by an overhead crane. After being charged, the roof closes and the electrodes are lowered in place.

During operation, a strong electrical current passes through the electrodes, creating an electric arc that generates a high level of heat and melts the scrap metal. With the addition of lime and fluorspar as fluxes, oxygen is blown into the melt. These additions are used to initiate chemical reactions that remove impurities, forming a liquid slag.As the steel is being melted, continuous sampling of its state from the molten can ensure that chemical composition and temperature specifications are met as per customer requirements. When the perfect composition and temperature are met, the molten metal is immediately poured from a ladle for downstream processing.

After tapping, the molten steel is often further refined with various alloy materials through multiple secondary metallurgy treatments (secondary steelmaking processes) such as degassing and ladle processing. The processes are; argon ladle stirring, powder injection and wire feeding capacity, vacuum degassing and ladle arc heating. They help ensure consistent temperature and uniformity (temperature, composition), adjusting to target specifications as required by the customer; removing contaminants such as hydrogen or elements down to low levels of ppm in certain steels.

Because of this, EAFs are known for their extensive power to produce steel in gobs up to 150 tonnes per melt. This makes them valuable resources in mass steel production operations. The flexibility of EAF process allows steelmakers to quickly respond to various market requests and utilise scrap as the main feed material, leading to sustainable steel manufacturing.

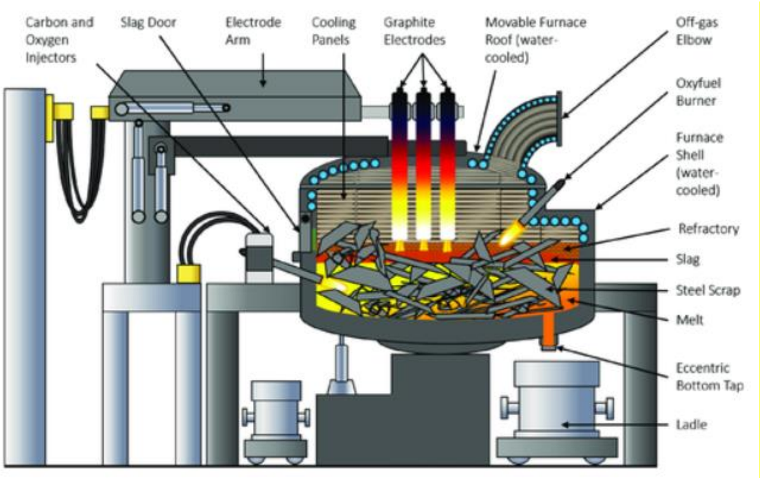


Figure 4. EAF.

5. The differences between EAFs and other processes in terms of technology

Understanding the key differences between other steelmaking techniques and EAF is necessary to measure both what EAFs excel at and where they are limited. By melting scrap steel with electrical energy, EAFs are more flexible and have lower capital costs than integrated mills using traditional blast furnace-basic oxygen furnace (BOF) technology that produce their own raw material from iron ore and carbon-based fuels.

In terms of reducing emissions and rates of recycling, EAFs are also more environmentally friendly than BOFs. These differences in technology are fundamentally important when considering how to compare the efficiency and sustainability of EAFs in steelmaking.

5.1. Pricing advantage

There may be some similarities between these modern technologies, but there are specific details that make EAF a more sustainable, economical and cutting edge technology. Let's review and compare them with each other in each subject again:

Today, EAFs offer unique economic, environmental and operational advantages that set them apart in contemporary steel production. From an economic perspective, the cost of $300/ton of capacity to set up a new EAF is much lower than the nearly 4 times more expensive basic oxygen steelmaking (BOS) and blast Furnace in integrated mills, which are at about $1100/ton.

Electric arc furnace minimill operators benefit from enhanced flexibility during business cycles. This pricing accessibility enables steel makers to swiftly enter the market at scale. EAFs offer the capability to quickly adjust production to accommodate a wide range of steel grades, promptly meeting changing market demands without the need for extensive retooling and disruptive downtime.

5.2. Environmental Sustainability

Electric arc furnaces (EAF) are a much cleaner source of steel production when compared to traditional blast Furnace and basic Oxygen Steelmaking (BOS), and have distinct advantages, such as being more versatile operationally.

One of the key benefits is lower greenhouse gas emissions. Since EAFs are electric and fed with a low-carbon electricity intensity (especially as the share of renewable energy sources increases steadily), their production process has much lower CO2 emissions than the other two. This movement in favour of cleaner energy sources is positive for EAFs, as they could conceivably run with an overall significantly lower carbon footprint than competing conventional steelmaking methodologies.

They are also key to recycling and the circular economy. Their primary input material is scrap metal, which not only reduces the amount of waste sent to landfills but also contributes to resource recovery. In addition to reducing the need for virgin raw materials, domestically sourced scrap metals have not been fully absorbed by traditional blast furnaces in recent years, and this will directly increase feedstock consumption at steel plants. As a result, scrap metal accounts for roughly 75% of the total cost to produce steel in EAFs, highlighting both the economic and environmental significance of incorporating recycled materials into green steel production.

Still, EAFs allow steelmakers to respond quickly to market shifts as well. They provide the flexibility to make a broad range of steel grades and readily adjust production volumes without time-consuming, laborious retooling steps. In a fast-moving market like steel, that agility makes a huge difference.

5.3. Operational perspective

In that environment, no other production method can compete with electric arc furnaces (EAFs) in the combination of their raw material flexibility and quality steelmaking capabilities. Their fast start-up and shutdown cycles are one of the major benefits EAFs bring to an operation as they allow for high operational efficiency with low downtime. With this flexibility, steel producers can more readily respond to market changes and the needs of customers with optimised production schedules.

The electric arc process of EAFs also allows for precise control over the temperature and chemical composition of molten steel. Steel grades demanding high-quality standards like those utilized in the automotive, aerospace and construction industries are produced very well through EAFs. This level of fine-tuning that can be performed in real-time to the temperature and chemistry of the steel helps ensure desirable final properties, especially for applications where performance and reliability are critical.

EAFs are also fully compatible with downstream ladle refining and vacuum degassing operations. Extra steps are necessary to create cleaner steel by removing contaminants and inclusions that could lower the quality of the finished product. Ladle refining provides further chemical composition adjustments while meeting the tightest oxide inclusion requirements. Vacuum degassing, meanwhile, eliminates gases that have been dissolved in the molten steel to enhance its mechanical performance and lower concerns related to porosity or hydrogen embrittlement.

These processes are integrated with EAFs to improve steel quality as well as steel weld ability and elongation. A cleaner steel offers better elasticity in the building and ultimately, more resilient products for more demanding applications. This is crucial for applications where strength and performance are paramount, such as in bridges or skyscrapers, amongst other critical infrastructure requirements.

Chapter 2:

EAF for Steel Production

1. Introduction

Electric Arc Furnaces (EAFs) are crucial in modern steel production due to their environmental, economic, and operational advantages. They reduce carbon emissions by using electricity, often from renewable sources, and recycle scrap metal, making them more sustainable than traditional methods. EAFs are flexible, can produce various steel grades, and adjust quickly to production demands. Their lower capital investment and advancements in automation and control systems enhance efficiency and cost-effectiveness, positioning EAF technology as essential for the future of steelmaking.

In the last chapter, we reviewed details about why EAF is more suitable for steelmaking when environmental, economic and operational aspects are taken into consideration. Given that the world is paying ever more attention to being sustainable and environmentally conscious, EAF technology also holds its own when it comes to helping reduce carbon dioxide emissions. Since EAFs run on electricity, which can come from renewable sources and rely primarily on scrap metal, they are much cleaner in terms of steel production carbon footprints. This move towards sustainability supports global efforts to fight climate change and reduce industrial greenhouse gases.

EAFs are highly flexible and adaptable to meet the demand curve of future markets. Their flexibility in switching between production processes for a broad range of steel grades, from standard carbon steels to sophisticated high-alloyed steels, will be key when industries change due to new demands on modern applications. Due to their ability of switch quickly on and off, EAFs can be started or stopped in minutes. This makes steel production a more responsive industry, especially when high efficiency is required from both a usage perspective (less waste) and reduced emissions.

From an economic perspective, the lower capital intensity of EAFs compared with traditional integrated steel mills will continue to be meaningful. With advancing technology, the price competitiveness of EAF operations is likely to be enhanced. Advancements in intelligent control systems and automation will play a role in optimising productivity, reducing energy intensity and improving the quality of steel products. The end result will be similar quality and reduced overhead costs since all of these improvements are moving the production process up in terms of standard.

2. Electric arc furnace development

Technological advancements, the quest for productivity and energy efficiency as well as environmental considerations, have redefined the evolution of electric arc furnaces (EAF) over time. In this section, we explain how EAF technology began and what developments it underwent to reach its current high performance.

2.1. Pre-1960s (earliest development)

Unlike the first-gen Electric Arc Furnaces (EAFs), which were fairly simple in terms of design and function, the furnaces, with transformer capacities up to 250 kVA per tonnes of furnace rating and the power cables connected to them, provided sufficient electric current to match internal resistivity, allowing for a production rate of 15-20 tons/hour.

These furnaces were lined with heat-resistant refractory materials like magnesite or dolomite that could provide the necessary resistance. The roofs were initially built from silica, but subsequently redesigned to use alumina materials with higher aluminium oxide (Al2O3) levels for better longevity and light-blocking performance.

As we have seen throughout the discussion, until the 1960s Electric Arc Furnaces (EAF) in their early stages operated with a particular structure that at first glance, seemed outdated for modern steelmaking processes. Above all the metal bath was oxidised with iron ore or scale to remove impurities, which are prerequisites for making good quality steel. The metal needed to be melted down, a process that used to consume approximately 3 hours of the production cycle.

The tap-to-tap time, including charging scrap, tapping molten steel and setting up for the next batch, was between 4-8 hours. In the early days, EAFs experienced a fast and uneven consumption of refractory linings, which forced owners to frequently maintain or change them in order to keep their plants operational. The early days introduced these essential traits, leading to further innovation for improving and heightening efficiency, productivity and consistency in electric arc furnace technology.

2.2. Second Generation (mid-1960s to late 70's)

The 1960s and 1970s saw EAF developments of significance a second generation, so to speak. These furnaces, and later versions developed by pioneers such as W.E. Schwabe, were instrumental in transforming the design and operational efficiency of this equipment. Schwabe's inputs were mainly in the area of developing and applying technology that substantially increased design efficiency throughout the secondary circuit and power, improving furnace performance overall.

At the same time, we have seen a dramatic increase in transformer unit capacity, which has gone from 250 to 450 kVA per tonne of furnace. The large upgrade, led to a dramatic increase in productivity, producing and able deliver new steel volumes by 25-40 tonnes per hour. This increased capability both satisfied the burgeoning industrial need and provided a stronger foundation for more efficient steel-making practices, leading to greater production.

High-power technology (HP) marked a milestone in the evolution of Electric Arc Furnaces, with significant advancements within operational characteristics. This period served to further refine things, like slimming down the electrode circle diameter for an enhanced current flow dynamic while reducing loss in energy. The Arc voltage drop and current peak value increase, improved energy efficiency and extended the life of critical components such as graphite electrodes.

At the same time, organisational changes to increase uptime and productivity were put in place that decreased operational breaks during charge loading as well. These modifications provided a more efficient EAF steelmaking process in general by reducing the complexity of operations.

Thanks to these developments, EAF steelmaking operations have gotten more efficient, but with that efficiency came increasingly sophisticated control systems and the requirement for similarly integrated operator training in how those state-of-the-art technologies can be managed most effectively.

2.3. Third Generation (1970s - 1980s)

The third generation of Electric Arc Furnaces (EAFs) was established during the period from 1970 to 1980, marked by much larger capacities and operational efficiency improvements.

The size of transformers also increased during this time, including capacities ranging from 450 to 700 kVA per tonnes of furnace capacity. Following this upgrade, EAFs made significant increases in productivity and could make between 50 and 80 tonnes of steel per hour. These improvements in transformer capabilities were essential for keeping pace with growing steel production demands and improving the efficiencies of steelmaking.

The third (like the second) generation of Electric Arc Furnaces EAFs included some novel and sophisticated design features, important for steelmaking technology. However, the Ultra-High Power (UHP) technology allowed a much larger current intensity, which improved operational efficiency dramatically. Relatively more heat efficient systems for walls and roofs involved water cooling, reduced wall thicknesses, extended refractory life and enhanced furnace operation.

Foamy slag technology was applied in the refining process to maximizing steel quality and decrease energy consumption. Eccentric Butt Wall Tapping has increased productivity for steel tapping and resulted in fewer steel oxidations, improving final product cleanliness. At the same time, environmental and operational modifications were aimed at sustainability and effectiveness concerns. In this era, dust collection systems were installed in order to treat gases, improve air quality as well as met environmental guidelines. By implementing operational optimisation to reduce unit manufacturing costs and energy consumption, the project enabled economic and environmentally sustainable steelmaking via an electric arc furnace.

2.4. 4th Generation (1980s to Present)

The Fourth Generation of Electric Arc Furnace(EAF) technology has marked a period that is defined and promoted by dazzling technological achievements combined with operational sophistication that continue to reshape the face of contemporary steelmaking.

In modern EAFs of this generation, transformer capacities in excess of 1,000 kVA per tonnes furnace capacity are common. This improvement has allowed these blast furnaces to reach exceptional production levels, exceeding 100 tonnes of steel per hour. The development of super ultra-high power technology has also promoted the steel production capability.

This period has been notable for considerable attention to operator working conditions in an effort towards the development of more effective automatic control systems and secondary metallurgy practices. Such enhancements have been instrumental in improving the operational efficiency as well as the safety and accuracy of several steelmaking processes.

Modern-day EAFs have also incorporated improvements that are advantageous for the environment and make them more sustainable. Now contained within dust- and soundproof chambers, the furnaces effectively control emissions as well as reduce noise levels. To minimize this negative environmental impact, off-gas heat utilization systems have been developed to increase energy efficiency. Additionally, greater emphasis is placed on scrap preheating and charge conditioning to maximize material efficiency as well as energy utilization.

Supporting these environmental improvements, major technical advances include the implementation of direct current (DC) electricity in furnaces that reduces grid impact and consumption of electrodes-making it operationally more sustainable. An additional factor that has helped to lower the environmental footprint is a combination of improved materials and design optimizations, which have contributed to higher energy efficiency, as well as longer life for refractory linings.

Electric Arc Furnaces (EAFs) have made substantial progress in performance indicators over the last five decades. Energy consumption has also drastically reduced from 630 kWh/tonnes in the 1960s to circa 300 kwh/tonnes in a modern EAF, as well as energy recovery and other technological enhancements.

Similarly, graphite electrode consumption has plummeted from 6.5 kg per ton to around 1.5 kg per ton as a result of advances in the technology and operational practices associated with electrodes. Minimized tap-to-tap time, likewise dropped from up to 180 minutes to roughly 45 (between-production-cycle quality and efficiency). These include oxygen blowing for metal oxidation, ladle metallurgy to further refine steel, water cooling system and more. They aid a very various level in improving the energy efficiency of electrical arc furnace operations enhancing their performance and using key tools to improve work process management like gas-oxygen burners.

In conclusion, Electric Arc Furnaces or EAFs have become more complicated over time due to technological advancements. With improvements in EAFs, the systems themselves have become more complex and require a greater degree of skill to manage. Such enhancements have complicated the operation of EAFs, with improved current flow dynamics, reduced energy loss and an extended life for vital components like graphite electrodes. Further, organizational changes to orient towards productivity create layers of operational complexity. Thus, the necessary integrated training for operators is critical to guaranteeing safety, highest performance and technical control of the sophisticated electric steelmaking process in modern EAFs.

3. EAF major components

The three main components of an Electric Arc Furnace (EAF) are the furnace itself, mechanical drives and electrical systems. The furnace is a closed chamber inside which steel melts and it made of a steel shell lined with special bricks. The top of the furnace is punctured with holes for electrodes, as well to release gas. The mechanical portions consist of the tilting machines for the furnace, the roof moving device and the Electrodes handling system.

Parts such as transformers and controls, which dictate the amount of power supplied to the furnace are all made from electrical equipment. A concrete base that shimmies on rocker-shaped steel supports allows it to rock thanks to hydraulic cylinders.

To melt the steel, electric arcs are created using graphite electrodes, which poke through holes in the roof. The transformer connects the electrodes and there are flexible cables for this purpose. Everything is designed to produce steel in an efficient and safe way, with facilities for gas cleaning or dust separation ensuring environmental compliance.

3.1. Reaction chamber

The effectiveness of an EAF reaction chamber in steel production is primarily determined by its size and shape, rather than the presence of any product other than the required slag-forming material. Besides steel production, the crucible can also be used for other purposes depending on the furnace size.

The conical-spherical hearth forms the lower chamber, designed to contain one heat's worth of molten steel and slag. This design means the tap is flowed properly during tapping, see depth-to-diameter ratio (d) 4.0 to balance between bath depth and protection shells. This allows an angle of 30-45° from the horizontal plane so that metal and slag can freely flow to the outside.

Chamber height is determined by furnace capacity, aiming to reduce heat losses and electrical consumption where the arc performs best, as well at optimizing roof life. These parameters are critical for tailoring EAFs according to the steelmaking needs, and improving operational efficiency. The proper design of the EAF reaction chamber allows for more efficient steel production, reduces energy consumption and improves overall performance.

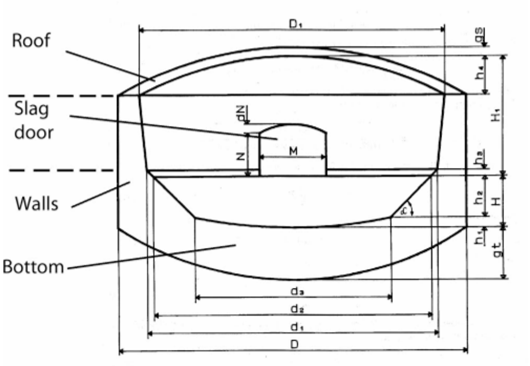


Figure 5. Diagram of a cross section of an electric arc furnace vessel.

3.2. Furnace shell

The furnace shell in electric arc furnaces (EAFs) is an important structural element that withstands the pressure exerted by the refractory linings and confines molten metal and slag. The shell is a single-piece design with an upper part in the form of a cylinder and a lower spherical part where the hearth (furnace) bottom with banks is mounted.

The shell structure is subject to both the static loads from its own mass and weight of lining material. in addition, dynamic charges during a period of charging operations. The shell is made of welded steel plates measuring 20 to 40 mm in thickness, with the bottom being thicker than adjacent sides by around 2-5mm for increased mechanical strength.

Externally welded vertical and horizontal ribs in the body provide a robust framework for supporting mechanical loads associated with thermal expansions and temperature variations within the furnace.

On the upper surface of the furnace housing are two critical apertures, generally comprising a primary door and molten metal pour spout for serving different operating purposes. The circular cross-sectional shape of the reaction chamber mainly depends on furnace size, process demands and design details.

It is dedicated to urgent operational tasks including temperature measurement, sample taking and the installation of devices like oxygen or coal lances. Support with water-cooled flange for temperatures of up to 450K. The taper-trough back pouring spout has a refractory lining, which guides the molten metal during tapping operations to ladles.

In modern EAF designs, the bottom shell is either a complete part or more often a set of removable panels (like water cooled walls design) that are connected by a flange around their full perimeter to allow maintenance and repair.

As examples of many ages that would have a pouring spout, modern EAFs today use the eccentric bottom tapping (EBT) system to perform more efficiently and safely which discharges the liquid steel from an impermanent opening at its base. They highlight the progress made in improving EAF design with respect to maximizing performance, maintenance and operational flexibility for steelmaking.

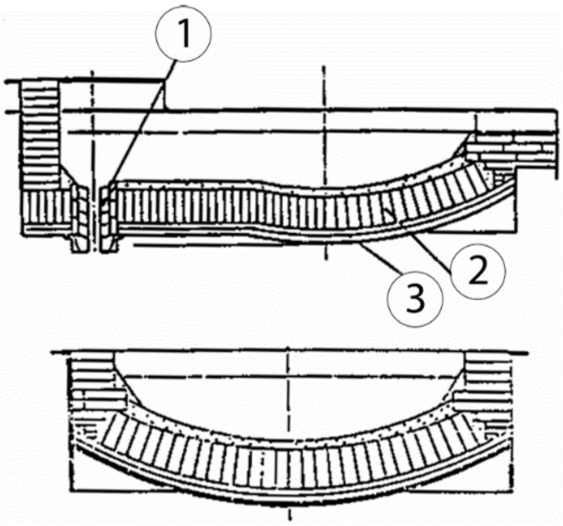


Figure 6. Side view of furnace bottom – EBT type: 1 – taphole, 2 – bottom refractory lining, 3 – bottom shell.

3.3. Refractory lining

Electric arc furnaces (EAFs) require high structural performance to avoid the honeycomb effect and molten metal leakage during steelmaking, making the refractory lining of the furnace bottom application extremely important. It is made up of three unique layers: insulating, protective and operational, each of which has a particular purpose.

An insulating layer directly on the furnace shell provides thermal insulation to keep outer shell temperature under 150 °C. Usually 10-30 mm thick it reduces heat transmission to the shell.

The protective layer above the insulating layer is usually made up of magnesia bricks with a thickness of 250-300 mm. It acts as a seal, preventing molten metal from going through the lining in the event of the destruction of the work lining. Its role of protection is further reinforced by the bricks that are dry-laid with gaps filled with magnesite powder.

The working layer made of magnesia or magnesite-dolomite materials with a special grain size is the part directly exposed to liquid metal in the refractory lining. This monolithic layer, 400-600 mm in thickness, maintains cleanliness and safety during steel production.

The total thickness of the lining with a furnace hearth, specified here for an approximate size furnace range from 500 to 1,000 mm, provides an extended working life of several thousand heats, which is possible under ideal operating conditions due to the stable thermal environment and reduced slag erosion experienced in service.

Older furnaces have a tap hole where banks meet the wall (opposite main door) for steel tapping, but it is highly erodible, and subject to corrosion. Modern designs incorporate a tap hole in the bottom (balcony) part of the hearth, assisting lateral steel flow more effectively with competence for 150-250 heats.

The furnace bottom also has porous plugs which help in the injection of inert gas at an effective rate to agitate the metal bath. Pot plugs, created with magnesium-carbon materials and which have internal gas flow pipes allow optimal stirring conditions in steel production.

3.4. Water cooling

Growing power supply transformer capacities represented a significant challenge in keeping the furnace wall and roof refractory linings on electric arc furnaces (EAFs) at their correct operating conditions. This required the introduction of water-cooling systems, which further increased lining durability and enabled higher-capacity transformers to be applied without compromising furnace wall conditions. Water-cooling, especially for larger furnaces, has been a common practice since the 1970s.

3.4.1 Water Cooling Panels

The magnesia-cased panels now may constitute up to 70% of the wall surface, with refractory bricks in the upper portion directly above the slag line and around the tap hole. Water cooling panels are usually pie-shaped sectors that mimic the geometry of a furnace.

Panels are provided with separate water inlet and outlet connections, which can be interlocked to adjust any of the four regions or all at a time through controls for variable flow rates to stabilise cooling temperatures across furnace paths.

Water-cooling panels have a refractory material, usually magnesia or a magnesite-carbon-based layer to insulate them from the thermal energy of an arc generated by electric current. Refined designs incorporate panels with grooved internal surfaces to prevent damage to the refractory lining when under extreme thermal loads.

3.4.2. Layered Cooling System

The layered cooling system for electric arc furnace walls combines the use of water-cooled elements with refractory materials. They are made of welded steel plates, and each is interspersed with magnesite products. This combination keeps the refractory cool over an electric arc.

3.4.3. Tubular Cooling System

The tubular system is a popular design for EAF-wall cooling because of its efficient heat transfer and the small area allocated to cold spots. Two predominant pipe configurations are employed: panel type or horizontal concentric pipes' circumferentially arranged around all the furnace walls. The panel system is the most common type and consists of a regulated intake and return balance point for each cooling system. To minimise variation in panel temperature associated with non-uniform heat generated by electrical arcs on the wall periphery, flow parameters of water are adjusted to provide even heating across.

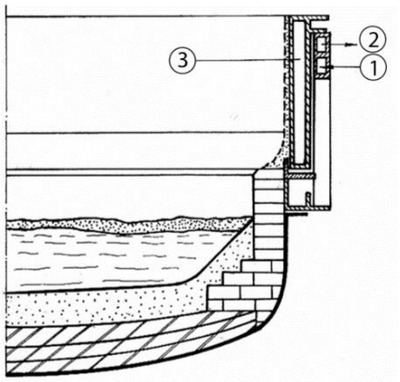


Figure 7. Example of water-cooled panel application in the hot zones of an electric arc furnace: 1 – water in, 2 – water out, 3 – water-cooled panel.

3.5. Roof structure

An Electric Arc Furnace (EAF) is a furnace consisting of an outer shell, surrounding the graphite electrode, and a hoist-able roof that can be removed for charging and maintenance. The main advantage of an independent mount is that it can be lifted and replaced easily. Most modern EAF roofs are water-cooled to resist the incredible heat produced during steelmaking. They are round structures, fixed down with a steel roof ring, often water-cooled to provide an extra independent feed of fogging water. Some designs of roof rings have internal partitions to promote moisture contact.

Both operation and transport are handled by hooks from which the roof is suspended; these feature part of a structural frame. Hydraulic cylinders provide the roof with lift and swing, these are movements whose ranges go from 200–400 mm in height up to an angle between swinging angles of 80° a +100 ° typical for charging. Roof base seal with flanges encloses furnace walls.

The roof has three holes to let in larger-diameter graphite electrodes so they do not get stuck and vent the gases. A fourth hole is used for off-gas evacuation. The roof is also water-cooled, covering approximately 85% of the surface and leaving only a near-electrode area in the refractories. Coaxial pipe or plate-based water cooling panels or tubular systems are used for consistent cooling and to provide less mechanical or thermal shock. The electrodes are armoured with insulating refractory layers in order to avoid electrical arcs or short-circuits and not generate unwanted eddy currents between the electrodes and metal panels.

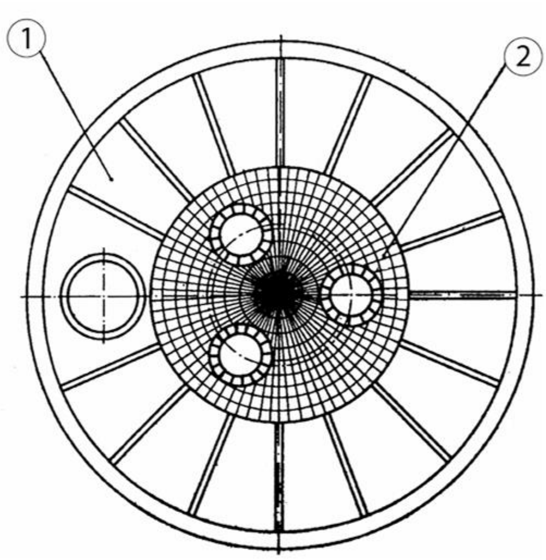


Figure 8. Design of the roof: 1 – middle part made of refractory materials, 2 – water-cooled segments.

4. Mechanical equipment

The bottom of the furnace must be particularly strong, being concreted in a monolithic manner under heavy loads with refractory bricks. The furnace rocker takes the entire weight of the roof, electrodes, operational mechanisms, as well as other components that are exposed to high temperatures in the steelmaking industry. This structure holds a plinth, which stands on mounted antlers with steel rails.

The most widely used foundation design consists of two bases separated by a path for a car track. The layout enables the space to be used in an effective manner and allows productive movement during steelmaking processes.

The furnace tilt is usually about -8° for slag removal and +5-6° for tapping molten metal. For the proper safety and functionality of operations, smooth tilting is essential, raising the need for such mechanisms that are effortless to operate with stability.

Tilting has long been accomplished by a hydraulic drive, providing for smooth and uniform motion. There is a drive system with one for each rocker of the tilting mechanism, so that in case one fails, the other can still be used. Additionally, the design prevents rockers from sliding against rails, proving stable functioning even for heavy loads.

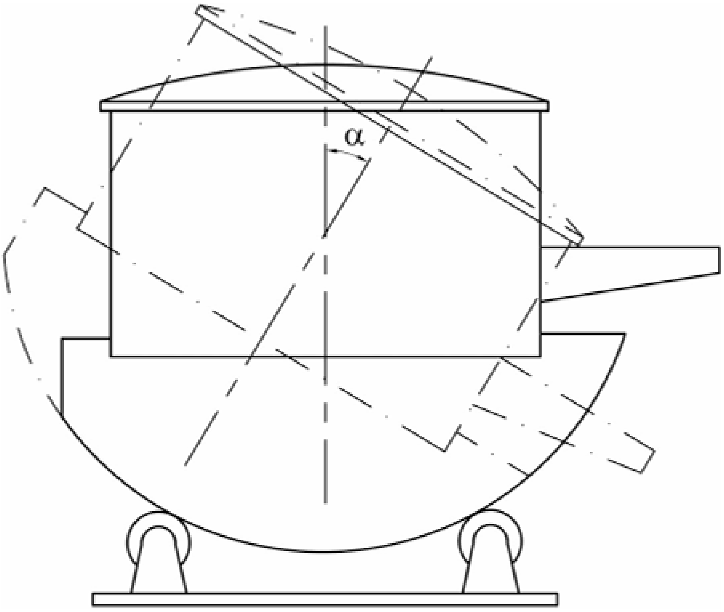


Figure 9. Design diagram of the roller-type furnace tilting mechanism: continuous line – the furnace in the operating position, broken line – the furnace tilted by an angle α.

5. Electrical equipment

Electric arc furnaces (EAF) have the energy saving advantage of requiring only 300 to 700 kilowatt-hours per tonnes with theoretical minimum consumption around 450 kWh/t. However, they require massive capital costs and are vital in production mills instead of mini-mills.

The electrical energy is mostly converted to heat energy, in the electric arc itself, which heats up water used for driving metallurgical processes and compensating for some of the losses typically found during steelmaking. To maintain consistent operation, EAFs are fitted with tailored power supply systems and electric arc control system for real time tracking of steelmaking process.

5.1 Power Supply System

Power stations are generally located some distance away from EAFs, and therefore the voltage level used to minimize electrical losses during transmission varies depending on furnace size:

- Mean voltage high: 15 to 30 kV
- High Voltage: around 110 kV
- Ultra-High Voltage (220 to 400 kV)

The power supply system for electric arc furnaces is made up of a primary circuit, a furnace transformer and a secondary circuit. The disconnect and operation switches of the power supply are placed here, at upstream in the primary circuit.

This furnace transformer down-converts the high grid voltage to a low, process suitable voltage for EAF. The secondary circuit with bus bars, bridal cables and tubular buses is responsible for connecting to the graphite electrodes downstream, which aid in electric arc formation. A well-designed transformer results in stable, efficient power delivery with minimal energy losses and optimal furnace performance across all voltage levels and configurations.

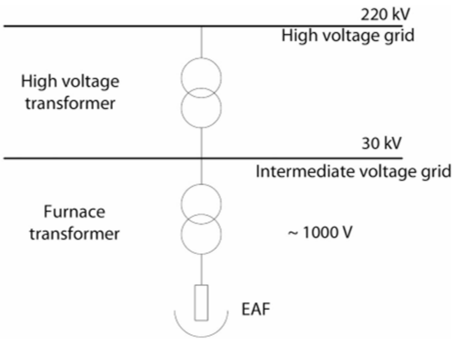


Figure 10. Schematic diagram of the electric power supply of an electric arc furnace.

5.2 Furnace Transformer

An Electric arc furnace (EAF) transformer consists of a magnetic core on which primary and secondary winding coils are wound. When an alternating voltage is applied to the primary windings, it produces a magnetic field inside and around the coil, mainly focused in the nucleus because of its high-magnetic permeability. The secondary winding is thus subjected to a magnetic field in which an electromotive force induces voltage on its coil terminals.

6. Auxiliary equipment

Auxiliary equipment plays a critical role in enhancing the efficiency and performance of Electric Arc Furnaces (EAFs). These systems help to optimize temperature distribution, improve melting processes, and manage by-products effectively.

6.1. oxygen-fuel burners

EAF faces the challenge of achieving a uniform temperature distribution throughout the vessel. The electrodes generate thermal energy (electric arcs), which represent local heating source regions.

The arcs are prone to "blow back" and maintaining the electrodes straight and extending their metal stick out, can cause uneven heating of the scrap charge, which is also referred to flame melting. In this process, the central region gets melted first, while zones near furnace walls melt slowly. This leads to the creation of different "hot" and 'cold spots in the vessel.

To address these temperature imbalances and accelerate the process of melting steel, additional sources of heat are installed at specific locations within EAFs in the form of oxy-fuel burners. They burn natural gas (or sometimes fuel oil) and are placed in areas with cold spots within the furnace. Such systems are located at the main door, lateral walls, and above the taphole for optimum utilisation of the heat.

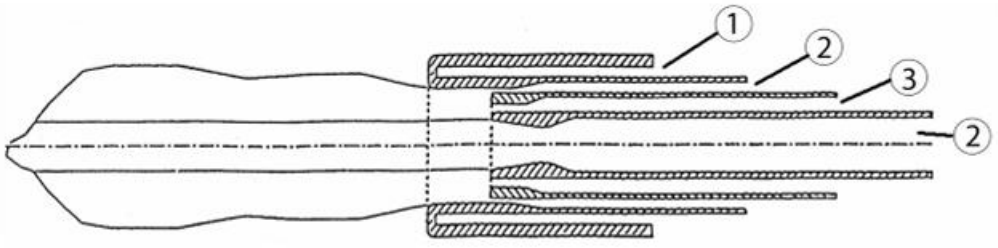


Figure 11. General diagram of an oxy-fuel burner section: 1 – water, 2 – oxygen, 3 – gas.

6.2. Post combustion by oxygen lances

Large quantities of gaseous carbon monoxide (CO) are generated during steelmaking in an electric arc furnace (EAF), mostly desorbed from bubbles existing within metal baths or slag.

Normally, these gases are sucked into the tailpipe, whisking them away to be oxidised into harmless carbon dioxide (CO2). Alternatively, there are solutions where the CO is oxidised to CO2 directly in the furnace chamber. This represents a significant exothermic post-combustion reaction that assists the melting process.

Post-combustion of CO emissions in EAFs is commonly completed using oxygen lances. Oxygen lances, typically fabricated from plain steel pipe of diameters ranging between 20-50 mm, blow oxygen into the furnace chamber.

Oxy-fuel burners can serve as post-combustion lances during late stages in some cases, depending on the setup. These burners have lower thermal power, from 2 to 6 MW.

6.3. Graphite Electrodes

Graphite electrodes are essential components in the Electric Arc Furnaces (EAFs) that feed power through the furnace roof into the beam inside to create electric arcs, which heat and melt scrap metal for steel production.

The cost-effectiveness of steel production in EAFs is strongly determined by the use of electric power and electrodes. The percentage of electricity and electrodes consumed per tonne of steel can also be precisely calculated based on total consumption.

During processing, the electrode materials are made pliable by binders, which are typically bituminous coal tar pitch with added anthracene oil to reduce viscosity.

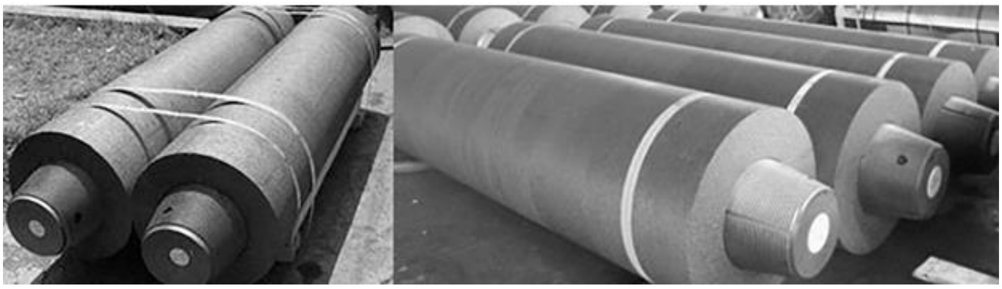


Figure 12. Graphite electrode sections

7. Operation cycle of EAF

The operating cycle for a typical or standard casting, as part of an already ongoing series of castings, can be synthesised as follows:

7.1. Preheating in the basket

The furnace tilts back to horizontal, and the tilt top-hole closes just as the ladle reaches a predetermined weight by weighing off residue. Scrap materials are deposited in the basket to correspond to various furnace tonnages.

In smaller to medium furnaces, baskets having dome segments hinged will be used for discharge by means of these pins inserted in recesses with ropes or snap locks.

There are electromagnetic grippers that grip the scrap and load it in the basket, making a precise matrix allowing for quick formation of the liquid metal bath and slag cover.

The charge composition, which consists of light scrap, carburising agents and lime has to be well-balanced in order not to damage the furnace lining and to ensure arc stability during melting.

Automated systems are widely used to improve the accuracy of scrap loading, with algorithms performed by real-time image processing. After loading the basket, it is placed over the furnace, and the shutter is opened to discharge the contents into the hearth for operation followed by closing of roof.

7.2. Charging phase

The positioning rails of the charging car ensure a guided take-in process without losing contact when getting into vertical position, once a precise working location inside the furnace, the connecting car is inserted into the opening and immediately starts to vibrate upon reaching the work spot.

While the system is still in manual mode for supervision, the job continues in "automatic" mode with a view to automation taking over prosecution of the process once an acceptable position is achieved for conveyance charging.

These ports are used to introduce oxygen and carbon insufflation, which leads to foamy slag formation on top and intensifies the furnace.

The system should run continuously in the post-combustion process. If necessary, to maintain a certain temperature of the furnace or outlet gas at an unacceptable level, it automatically included "high flame" mode. The aim is to obtain and maintain a bath temperature close to 1600 °C while controlling the charging speed.

If needed, scrap charging speed can also be manually adjusted on the furnace control panel by toggling a series of switches that change the system to "manual" operation. Switching back to automatic simply involves flipping a switch on the control panel, and this can be done during subsequent sessions.

During this phase, the key objectives are to keep bath recarburization at around 0.20-0.25% (2000-2500 ppm) combined with careful lance placement in order to achieve carbon flow into the bath and adequate post-combustion as well as slag formation.

7.3. Fusion

With the charge in place, the furnace is covered, and electrodes are lowered through retractable covers into position to initiate electric arcs between them and close unstable "craters" formed temporarily by liquid steel pooling on top of scrap pieces. This stage is critical in terms of power control, as it not only avoids a short circuit but also protects the furnace roof.

During the 8-12 minute charge phase, melting continues as arcs penetrate into more stable configurations, globally heating scrap until a liquid pool is formed. The melting cycle and further processing continue until most of the scrap has been liquefied, typically lasting 30-100 minutes per meltdown phase.

When oxygen reacts with iron, it forms (FeO) in its oxide form. This reaction occurs at the surface of hot iron scrap, which is by far the major source of thermal energy escaping from most incineration systems.

$2Fe + O_2 \rightarrow 2FeO$

Most silicon in the scrap oxidises to form ($SiO2$), which is a highly exothermic reaction and adds heat generation.

$Si + O_2 \rightarrow SiO_2$

Phosphorus oxide production ($P2O5$), which is helpful for transferring and separating the phosphorous content into slag, separates metal from the basic material. This reaction helps to reduce extra phosphorus, thus increasing the purity of molten steel.

$2P + 5O_2 \rightarrow P_2O_5$

Manganese (Mn) and chromium (Cr) respectively, are oxidised by iron oxide to form manganese Oxide (MnO) and chromium-oxide ($Cr2O3$).

$Mn + Fe_2O_3 \rightarrow MnO + 2FeO$

$Cr + Fe_2O_3 \rightarrow Cr_2O_3 + 2FeO$

The carbon present in the metal bath, oxidises to produce a bubble ($CO2$), giving out carbon monoxide (CO). As these bubbles rise up through the molten metal, it improves bath stirring and heat transfer efficiency. The CO bubbles have the important function of stirring the bath for uniform heating and heat transfers.

$C + O2 \rightarrow Co_2$

This process continues with injecting oxygen lances into the bath and overheating the scrap until the desired molten metal is obtained.

7.4. Slag removal

The slag, which primarily consists of oxides with impurities like carbon, silicon, phosphorous, and sulphur is controlled in the mould when the cast iron liquid centre reaches a certain height.

It serves as a vital protective barrier against the re-oxidation of steel and also absorbs further impurities at this juncture. Fluxes and additives are then added to help react with the impurities in order to remove them.

Operationally, the maintenance of the slag door and pit is required for proper operation. After the steel reaches a final composition and temperature, it is dropped into side lining mode by titling the furnace at -8°.

7.5 Casting into the Ladle

The process under the casting phase of Electric Arc Furnace (EAF) is carried out properly to assure a safer and more effective transfer of slurry steel into the ladle. The operator starts the casting operation from the casting console, manually opening tap holes and controlling furnace tilt.

First, the furnace is biased at some angle. usually around +5°, but this may change depending on how the flow of steel is desirable.

The tap hole shell opening is a regulated operation related to the poured steel weight to prevent overpour. During tapping, the operator carefully monitors the furnace tilt angle to control the flow of molten steel.

Chapter 3:
Operator Role and Training

1. Introduction

Skilled and trained operators are vital for the efficient and safe operation of Electric Arc Furnaces (EAFs) in the steelmaking industry. These operators play a crucial role in overseeing the entire EAF process, ensuring that each step is executed correctly and efficiently. Their expertise and decision-making capabilities directly impact the operational success, safety, and quality of the steel produced. This chapter delves into the multifaceted role of skilled operators, highlighting their importance in the smooth functioning of EAF operations.

The necessity of skilled operators cannot be overstated. Their comprehensive understanding of EAF technology and processes allows them to manage the furnace's complex machinery, adjust parameters to optimize performance, and troubleshoot issues as they arise. Operators must be adept at interpreting data from various sensors and control systems, making real-time adjustments to maintain optimal furnace conditions. Their knowledge extends to the properties of different raw materials, the behaviour of molten steel, and the dynamics of the electric arc, all of which are critical for producing high-quality steel.

Safety protocols are an integral part of EAF operations. The chapter outlines the rigorous safety measures that operators must follow to prevent accidents and ensure a safe working environment. This includes the use of personal protective equipment (PPE), adherence to standard operating procedures, and regular safety drills. The chapter also discusses the importance of maintaining a clean and organized workspace to minimize hazards. Emergency procedures are detailed, providing operators with the knowledge they need to respond effectively to incidents such as electrical faults, equipment malfunctions, and fires. These procedures are designed to protect both the operators and the equipment, ensuring that any disruptions to production are managed swiftly and safely.

Continuous training is emphasized as a cornerstone of maintaining high performance and safety standards in EAF operations. The steelmaking industry is constantly evolving, with new technologies and methodologies being introduced regularly. Operators must stay updated on these advancements through ongoing training programs. This chapter highlights the benefits of continuous learning, including improved efficiency, reduced downtime, and enhanced steel quality. Best practices in training are discussed, such as the use of simulations, hands-on workshops, and collaborative learning environments.

2. Necessity of having Skilled and trained operator in general for industry

Electric arc furnace (EAF) steelmaking relies on these skilled operators to ensure that operations run efficiently and safely. Their expertise and competency are the difference in many areas of importance that directly influence operational success and to some extent, safety.

In general, operators alone are the most important technology for achieving maximum operational efficiency in such countries. They have the skills and experience to tweak processing conditions, follow equipment output better, hence setting with precision for optimal productivity.

In EAF steelmaking, this implies monitoring the melting process, regulating gas flow rates, and performing efficient stirring in a molten bath. Highly skilled operators interpret data from sensors to increase production rates and reduce energy consumption, improving overall efficiency with real-time alterations.

Safety in industrial settings is always a priority, as steel mill operations normally involve high temperatures, heavy equipment, and dangerous chemicals. A skilled operator makes an enormous contribution to a safe work environment.

They are required to spot safety risks that might compromise the well-being of everyone at your work site, follow all safeguarding processes stringently and efficiently if there is an emergency. Their alertness and conformity to safety measures reduce risk, ensuring a safe working space for both them and their fellow passengers.

In addition, skilled operators are adept at preventive and basic maintenance of their machinery. All are inspected periodically, signs of decay are detected and equipment stoppages are prevented through this process, along with renewals or adjustments. Preventative maintenance through proactive management ensures high availability and plant productivity in this case with regards to the EAF.

Skilled operators also play a major role in quality control. To ensure satisfactory quality of steel, various important parameters like temperature; chemical composition, and slag formation are continuously monitored. Their outcome-obsessed precision and commitment to quality control guarantee that results reflect nail-the-spec product outcomes at the heart of steel mill baseload stability.

Skilled operators not only excel at technical skills; they also possess adaptability and a culture of continuous improvement. They adopted new technologies, applied process improvements, and followed work best practices to improve efficiency, by ensuring a competitive advantage. The adaptability brings innovation to the steelmaking process and ensures that it can answer market demand.

Experienced operators are also important for transferring knowledge and training on how to tackle various aspects. Quality training gives operators the edge to address issues when they arise and is ready for EAF steelmaking challenges with expertise on both intricate technicalities of steel melting as well as safety.

It means we are able to share knowledge, maintain operational consistency, and pass it down through the generations of operators acting upon our instructions, maintaining a high level of performance as well as continuing safety.

This chapter will detail an example of elucidating operational stages involved in Electric Arc Furnace (EAF) with BPMN modelling to help operators understand the steelmaking process more easily and safely.

Introducing EAF steelmaking by highlighting its central place in the world of modern-day steel production, stressing the need for trained operators to control and run their furnace effectively. The process was modelled with BPMN diagrams, and it has seven operational stages.

3. Safety protocols and emergency procedures

Electrical arc furnace (EAF) steelmaking constitutes a high-risk environment, which emphasises the necessity of imposing safety protocols and emergency procedures on EAF operators. Operators train hard and follow strict operational procedures so that they are able to overcome uncertain risks diligently.

Working with molten metal is a significant safety concern for EAF operators as well. Molten steel, for example, can be over 1600°C and so it has the potential to cause severe burns if not treated correctly. Operators are provided instructions for the use of personal protective equipment (PPE) which includes heat resistant clothing, gloves and face shields & safety boots. They are taught how to work safely with long-handled tools handling material close to the furnace door, working just out of reach of molten metal so they won't get burned by splashes or spills.

Another is the safe and proper control of electrode regulation in EAF operations. Operators control the placement and voltage of electrodes that create an electric arc between them, sufficient to melt scrap metal.

If electrodes are not used properly, they might lead to electrical hazards like arc flashes and sometimes minor electric shocks. It highlights the significance of keeping communication lines open among team members, following lockout and tag-out processes before electrode adjustments, and using insulated tools to prevent burns.

The EAF operator faces a whole new set of safety concerns working in a furnace to turn practice. The actual process of tipping the furnace to pour molten metal into ladles or slag pots needs high flow control for no spillage and operator safety.

Operators are rigorously trained with learning regarding the furnace tilt limits, necessities on its charge acceptance and assurance over safety interlocks for avoiding unsafe tilting operations. In the event of a fault or unsafe tilting operations, emergency stop facilities that would halt all operations directly are also provided.

In the EAF operation, environmental standards are certainly a major problem because of gas and dust emissions or fumes released in the of steel production process. Operators are versed in identifying and limiting such hazards by utilising ventilation systems, wearing necessary respiratory protection, and performing routine air quality checks. Their workers are also trained for the safe handling and disposal of by-products (slag, refractory materials) to reduce environmental impact.

Disaster preparedness is also one of the core trainings for EAF operators. Operators also participate in a routine series of drills and simulations to simulate emergency scenarios for evacuation, fire suppression, and first aid. This readiness is important to make operators ready for an immediate and effective response in an emergency that may arise, reducing the possibility of a damages which could result in loss of life on-site.

In this way, EAF operations is advocating for a regular advance in safety practices. Through dedicated operator participation in safety committees and scheduled regular safety meetings, identified hazards are discussed, leading to shared best practices or suggested steps for trending positive improvements.

Management promotes a safety culture based on the identification of hazards, risk assessment and implementation of proactive safety practices in steelmaking operations to ensure the health and welfare of all stakeholders.

To ensure they operate safely within the confines of their operational context, operators are trained to follow strict safety protocols in compliance with international standards and directives (such as for machinery electrical safety EN 60204-1 or ATEX regulations specific to explosive atmospheres).

EAF operators are responsible for maintaining a safe work environment, rigorous safety practices and emergency procedures to ensure the efficient and reliable operation of electric arc furnaces.

Through their continued investment in safety, as well as ongoing training and continuous improvement efforts, Gerdau has been able to lead the way among steelmaking industries globally for its safety performance. This not only keeps people safe, but it also helps the mill run efficiently and sustainably.

4. Operator essential skills

The start-up sequence is crucial for successful steel production. Operators carefully inspect equipment and check furnace lining conditions to ensure everything is in working order. Adherence to standardized start-up protocols minimizes risks and optimizes furnace functionality from the beginning.

Scheduling the charging of ingots is crucial for optimizing furnace operations and ensuring steel quality. Operators must understand the characteristics of scrap in terms of size, composition, and density for each melt. By strategically combining scrap charges and timing them through different layers, operators maximize furnace capacity without sacrificing energy efficiency.

The primary tool for melting metal is an electric arc. Operators control the arc to maintain optimal conditions, moving the electrodes, ensuring arc stability, and adjusting power levels to melt steel evenly and efficiently. This requires an understanding of electric principles and high-voltage arc dynamics, which positively impact furnace performance.

After melting, operators refine steel chemistry to meet exact customer requirements. They fine-tune steel properties such as strength, durability, and corrosion resistance by adding alloys, fluxes, or other additives. Expertise in metallurgical principles and chemical interactions allows operators to create a product mix designed for market needs.

Tapping molten steel and starting casting operations are critical tasks. Operators schedule tapping operations to ensure metal purity, avoid oxidation, and enable efficient steelmaking. Timeliness and accurate coordination with ancillary personnel enhance casting operations and productivity.

Modern electric arc furnaces (EAFs) utilize advanced control systems and automation technology to improve operations and increase productivity. These systems allow operators to monitor process parameters, analyse data trends, and make optimized decisions. Data management, troubleshooting, and system diagnostics help operators quickly respond to operational challenges, ensuring minimal production downtimes and maintaining quality standards.

Operating EAFs successfully requires cooperation among operators, maintenance personnel, metallurgists, and others. Effective communication, information sharing, and mutual troubleshooting are essential. Teamwork, communication, conflict resolution skills, and leadership qualities are highly valued to achieve common production objectives.

5. Common Challenges Faced by EAF Operators

Confusion in Timing of Process: The timing of the process phases still remains a big challenge because it is difficult to see inside the furnace. Operators rely on their experience and external indicators, such as furnace sound or light emissions, all of which are subjective and not always reliable. The phase transitions, if delayed, lead to energy consumption inefficiencies and productivity losses, which eventually affect the performance of the furnace.

Wear and Tear on Equipment/Electrodes: High-temperature conditions inside the EAF ensure that refractories, electrodes, among other parts of critical components used in the EAF, are exposed to continuous wear. Electrode consumption, in particular, accounts for a significant part of operational costs and is compounded by the uncertainties generated during melting. Arc instability and other such factors cause wear on the torch, so maintenance is a very common and necessary task, causing more downtime.

Electrode Tip Breaks or Infrastructure Destroyed: The electrode tip sometimes breaks while you are starting the bore-in phase and can damage your furnace infrastructure. Apart from the costs of repair, production schedules are also disrupted due to these incidents, which underscores the necessity for monitoring systems capable of identifying scrap obstructions and optimising bore-in processes.

Estimating the scrap volume: Estimating the scrap volume loaded in the furnace is also a tough metric to estimate, as with wear and tear of the refractory lining and material buildup, the furnace conditions change regularly. A different amount of scrap changes the efficiency with which the process is melted and therefore demands a longer or shorter heating time, thus influencing productivity and energy consumption.

Problems such as Quality Variability and Monitoring: Since EAFs mostly use recycled scrap, quality variations in steel composition are intrinsic to the process. The conventional methods for quality inspection in the form of sampling the products become slow and give lower depth data points. Monitoring steel chemistry and slag composition is essential for efficient operation, resource utilisation, and product quality.

Automation Challenge: Due to the variability of scrap loads and limited real-time process visibility, automating EAF operations is an unbelievable job. Static process models cannot always fully resolve variability, which is why more adaptable control methods are required that can adjust according to the actual state of a furnace during operation. Optical Emission Spectroscopy (OES) and other real-time monitoring mechanisms, in fact, offer significant promise for providing high accuracy auto-calibration controls.

6. Primary responsibilities and tasks performed by EAF operator in steelmaking process

This BPMN file lists the main functions and actions taken by Electric Arc Furnace (EAF) operators. This BPMN diagram shows the whole life cycle of the EAF operation completely. Again, for the sake of clarity and to avoid an overly complex or ambiguous process, we break this down into six clear steps. The operation needs to take these steps.

The BPMN file describes in each step, which operations the operators must perform (based on their technical knowledge and industrial experience) during all six steps. As discussed before, after the slag tapping is completed, a fresh cycle must begin with the furnace significantly inclined from a vertical position. The cycle is completed when the taphole has been closed and an assessment of how much material remains in the furnace is made.

The elaborate decomposition into six stages aims to ensure that all the operations characteristic of EAFs are executed with precision and in systematic order. This allows for clarity and far better comprehension of their role to be achieved by operators methodically, helping to contribute towards the correct functioning of EAF.

This BPMN file provides direct operational guidance for operators with clear procedural instructions. The operator needs to have visual and performance based knowledge on how he/she is going through their EAF cycle steps.

6.1. Preheating

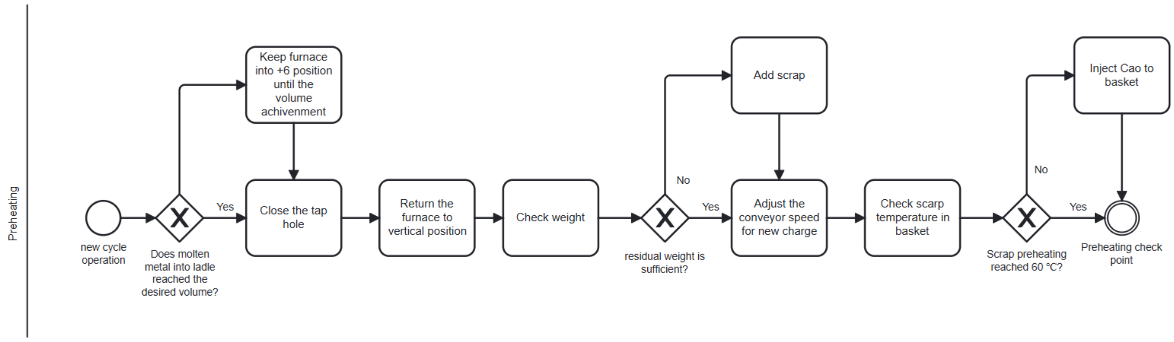


Figure 13. Preheating phase operator viewpoint operation.

One of the foundational positions in steelmaking, an Electric Arc Furnace (EAF) operator, is responsible for collecting, sorting, and getting scrap metal prepared. This encompasses recycling steel from a variety of sources, it has to be separated by size, composition, and cleanliness, then loaded into a basket.

After charging, the operator takes control of an important preheating phase, exposing the scrap to a temperature able to remove moisture and increase its temperature to close to the melting point. This preheating also shortens the melting time, and can save energy as well as considerably improve efficiencies in steel production. This can be done with a gas burner, an electric resistance heating element, or by using induction heating systems that take advantage of the hot excess gases from furnace operation. The addition of limestone (CaO) and the preheating of the scrap are carried out using resources to be used most efficiently.

Because they preheat their scrap to around 600°C for optimal quality output and continuously monitor the temperature during this process, casting systems normally use sensors or thermocouples that automatically control the feed of a conveyor as it adjusts its speed so it can adapt to every input using variations in moisture content.

To ensure a complete uniform temperature and heat profile while avoiding material deposits in the basket, panels run continuously. This means an operator is responsible for making sure the basket and conveyor system work correctly, interrupting it in such cases as when material sticks or if there are problems with the built-in detector, in order to ensure high quality screening. It is very important to control the conveyor speed because of the movement and capacity for transferring scrap metal into a car that goes in line with the funnel spout towards the furnace.

Quality assurance is strictly maintained during the whole process as the operator keeps an eye on the quality of scrap metal. These factors are measured for optimal melting performance in order to produce clean, high grade steel.

Lastly, the operator supervises the timely and controlled charging of preheated scrap into a high-powered electric arc furnace, thereby guaranteeing efficient melting for successful steelmaking. During these phases, the operator's experience and care may significantly influence the decision to run an EAF in an efficient way. They can adjust many parameters required for the proper operation of the furnace. These measures to monitor and manage production make it a steel of superior quality, demonstrating the commitment from both operator sides to becoming better at finding material.

6.2. Charging

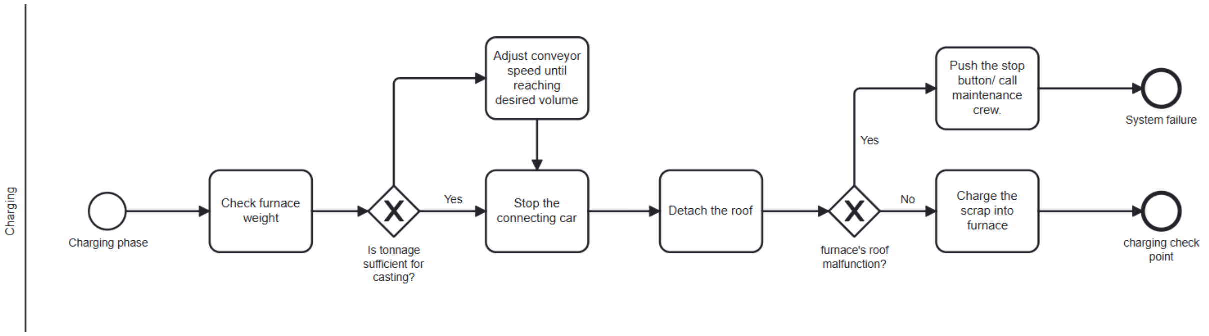


Figure 14. Charging Phase, operator view point operation.

During the charging step of an EAF, because the operator must help speed up related steelmaking processes, it is important that his intervention be stopped. The operator accesses critical information about what molten metal is still in the furnace from the previous cycle around 15% of the furnace's total capacity before charging begins. This allows the scrap to melt quicker, which has a beneficial impact on energy efficiency, as evidenced by lower metal stats after processing. The furnace will go into charge only after it is placed in the vertical position through manual confirmation by the operator. If it does, the operator can slow down or stop the connecting car via conveyor speed and hold until the final furnace position is achieved.

Once it is in working position, the connecting car starts vibrating automatically, and scrap can then be used for charging. Manually: The system is in manual mode. After the car is aligned as necessary, the operation transitions to "Automatic" mode, where everything will be run autonomously.

The scrap metal is added by spreading it over the charging layer in order to be heated and molten uniformly. More substantial parts create a solid bottom layer, while smaller pieces and fluxes are piled on top. Continuous monitoring through sensors and pyrometers is used by the operator to keep an eye on the internal furnace temperature, keeping in mind its ideal range for efficient steelmaking.

The charging is made at the operator's discretion by taking into account an array of parameters, such as the type and proportion of the scrap charge, the quantity needed, capacity, or space-volume dimension. Ongoing monitoring of hearth loading and melting temperature is mandatory for the efficient operation of any furnace.

Once the conveyor is stopped, the roof opens, and connecting cars are withdrawn in an ordered fashion to load up a furnace. If needed, scrap charging speed can be controlled manually to keep the best parameters.

The operator, by good command, sees to it that the electric arc furnace produces top-grade perimeter and conforms firmly to all regulations. This tactile experience is designed to showcase the best steelmaking processes and show care from the operator's side too for making quality time in steel production

6.3. Fusion

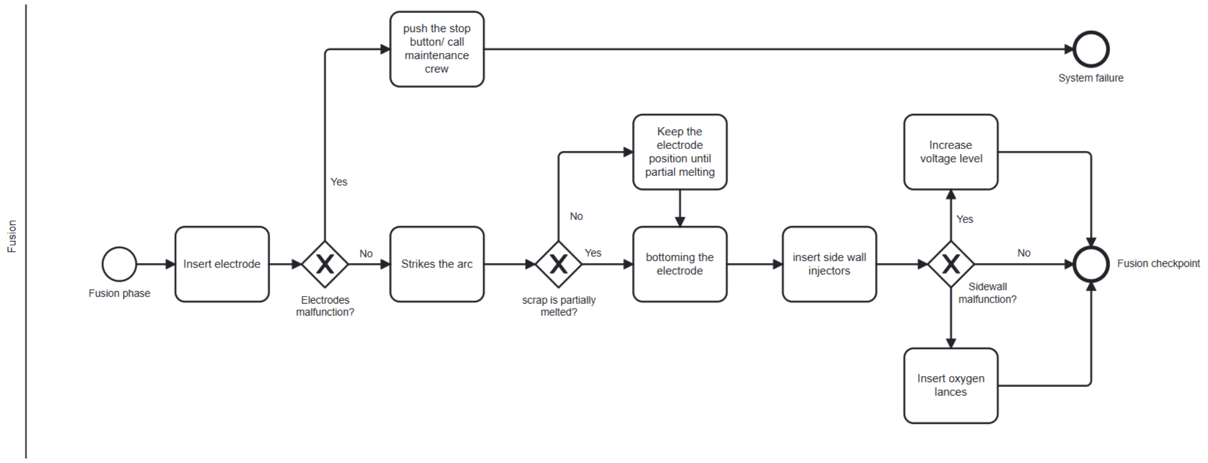


Figure 15. Fusion phase, operator viewpoint operation.

The operator first places the roof and loads graphite or carbon electrodes via these holes in the roofs. On top of the furnace, these electrodes are necessary for creating an electric arc when a current is passed between them. To prevent damage to furnace walls and roofs, voltage is first reduced to a very low value.

Once the charge has melted away, while it continues to melt throughout use for that job, an operator will remove a roof and add more under stress until they reach the target tonnage. This on-going charging status is very specifically controlled, either by casting these parameters as defaults to the system or unless otherwise commanded.

The system is designed to maximise production by varying the scrap feed rate according to constant furnace temperature measurements, so melt works efficiently without overheating or consuming unnecessary power. The bath temperature of the molten metal is checked every 6–8 minutes by way of a carbon test, which allows the operator to independently adjust scrap feed rates.

During the fusion process, an operator guarantees that the roof is correctly positioned for melting to start production; continually monitors furnace temperature, power demand, handling electrode position, and voltage. This is what ensures the electric arc furnace performs efficiently, produces good steel quality, and follows protocols while also contributing to improving the overall steelmaking process, which mainly depends on scrap procurement.

6.4. Decarburization

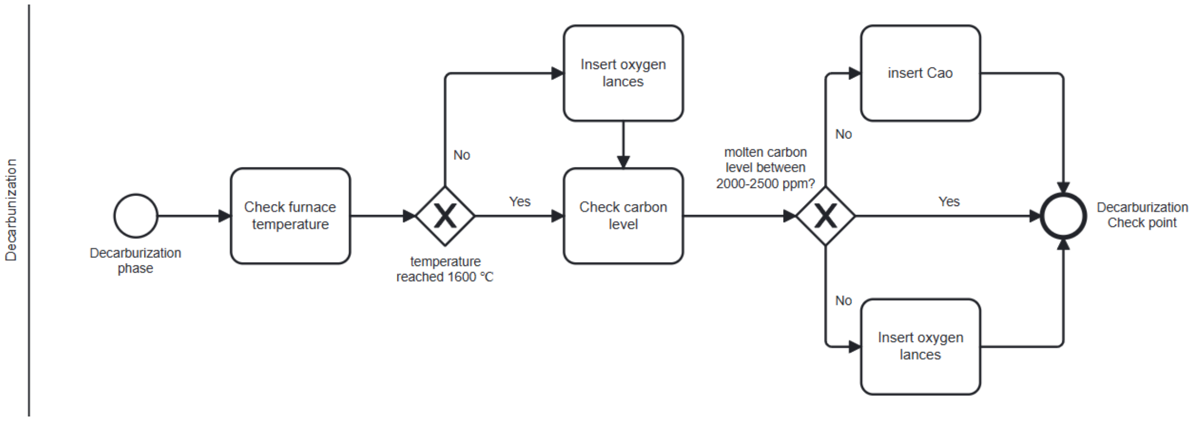


Figure 16. Decarburization phase, operator viewpoint operation.

Electrodes are fed into the furnace at a maximum charged depth, resulting in a maximal voltage and arc temperatures of 1500-1600℃. The operator handles both electrode positioning and melting. AC results in cold spots around the furnace, notably at the gap between the electrode and the bottom. Injectors burning carbonaceous fuel, typically natural gas or a derivative thereof, are used at the side walls to add heat and mix temperatures.

After achieving meltdown and homogenization of temperature, the operator then continuously injects oxygen into the mouth until the intended carbon content is reached at tap. The reaction of carbon with oxygen is an early stage decarburization process.

Carbon needs to be measured and controlled appropriately, as per the specific requirements of steel production. During the last overheating phase, less carbon is fed by the operator to give more accurate controls on its content in metal. Most of the supplied carbon is blown into slag to participate in deoxidation and thereby remove excess carbon and other impurities present in steel, improving its quality.

The operator is also able to monitor the quality of scrap metal fed into a furnace (typical size, content, and cleanliness) to ensure the best melt response set-up as well as the highest final product value. It is, therefore, crucial to monitor and control the carbon content in molten metal continuously so that it fits within a selected range, allowing the operator to visually check top quality by checking steel composition.

Its control system uses the furnace temperature and continuously calculated data to optimise automatically by adjusting the scrap feed rate, allowing efficient melting without over-temperature or high energy consumption. An operator performs carbon analyses daily and adjusts the scrap feed rate accordingly, monitoring bath temperature (melt) every 6–8 minutes.

Carbonaceous fuel injectors, like natural gas, are injected through the side walls of furnaces to raise the temperature. This prevents the operator from using these injectors in the wrong manner, which will prevent cold spots and also sustain furnace temperature at an optimum level.

Using these individual steps and a continuous checking procedure, the operator makes the electric arc furnace run correctly to give an excellent product of steel as per quality standards, adhering to all protocols necessary for the correct overall process.

6.5. Tapping

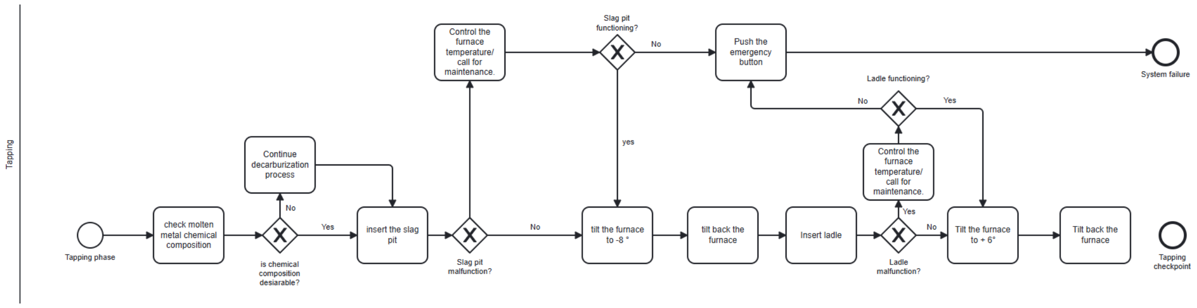


Figure 17. Tapping phase, operator viewpoint operation

When the scrap metal has melted away, the operator oversees the construction of a slag blanket, a layer that consists mainly of oxides created from impurities like carbon, silicon, phosphorus, and sulphur. The slag serves as a temporary protective layer, absorbing impurities and preventing the re-oxidation of the steel. To make this process easier, some fluxes and additives are also added by the operator, which react with these impurities to remove them.

In the melting process, oxygen is continuously injected by the operator into the molten metal until it reaches the desired carbon content. Managing and tracking carbon content is necessary to fulfil the specific steel design specifications. An operator performs periodic carbon analysis and adjusts the oxygen feed accordingly in a continuous tuning of the decarburization process.

At the end of steelmaking, after all composition and temperature targets are reached for the final heat (tap), the operator begins the tapping phase. The operator first raises the EAF completely to the -8° maximum tilt position, where the molten mixture is poured out into a slag pit. This step ensures the removal of slag and prepares the furnace for the next cycle.

Next, the operator controls the tapping of the molten metal into a ladle. This process is managed from the casting console, where the key selector is used to put the casting console into operation and start the casting process. The operator controls the tap hole opening device and furnace tilting from the console. To initiate casting, the operator tilts the furnace +5° or +6° (adjustable) to start the flow of molten metal. The controlled process of opening a tap hole is directly related to the weight of the poured steel for safety purposes.

The operator accurately controls the angle of furnace tilting to allow a smooth flow of low carbon steel, ensuring that no more steel or slag is coming through before moving forward. The operator also opens the door on the hole of the EBT (Electric Bottom Tap) panel and locks its movements. A tap hole inspection is performed to ensure there are no blocked steel pouring pathways.

After verifying that all conditions are met, the operator starts filling up the tap hole with sand and fills it above to ensure proper maintenance and safety. Throughout the casting operation, the operator maintains a steady watch, ensuring adherence to safety procedures and careful handling of the molten steel. Effective communication and organization with other operators and staff involved in the casting operation are essential to uphold the effectiveness and safety requirements of the steelmaking process.

Chapter 4:

Use of VR and Simulation for Training

1. Introduction

Simulation-based training (SBT) represents a vast opportunity in industry for using virtual environments that can be an imitator of real-world processes with great accuracy to train employees. This type of simulation offers user experiences with zero risk and negligible cost in comparison to real-time traditional learning. One of the most well-established kinds of SBT is virtual reality (VR), which has increasingly changed ways of training in many industries by creating a controlled environment that simulates real-world operational structures.

Simulation-based training has completely altered the way industrial training is conducted. Through the use of traditional VR training methods, the trainee can even understand how to operate in critical situations with respect to safety protocols. By introducing this new approach, trainees participate in learning scenarios in a virtual environment that simulates the complexities of real world operations. SBT involves trainees in a 360/VR environment for enhanced situational awareness of advanced learning and provides practice of essential skills securely and without consequence.

2. What is simulation?

In general, simulation is the imitation of an operation in a real-world process or system over time. It requires preparing a model that simulates the crucial aspects of system process activities or real-world operations and verifying and validating it. The simulation model clearly defines questions around the performance of any process to explore and analyse various scenarios that are beneficial for the knowledge of the trainee or impossible to test due to dangerous results in real-world cases.

It can also simulate complex assembly processes, machinery operations, and safety protocols, which are important to manufacturing. Staff can become skilled and confident through training under supervision, resulting in a more effective workforce with fewer occupational injuries. Trainees are able to perform tasks that reinforce their knowledge and practical skills by allowing them to do the maximum number of repetitions of procedures at increasing levels of proficiency.

In healthcare, for example, simulation-based training provides medical practitioners the opportunity to practice surgical techniques, interact with patients, or respond during emergency scenarios without fearing any losses. This not only improves technical skills in any field, but also enriches decision making and confidence.

In recent years, artificial intelligence (AI) and machine learning (ML) have also helped in simulation-based training to provide better results. Through this advanced technology, trainees are able to analyse the performance of AI algorithms to understand their strengths or areas for improvement so that personalised feedback and recommendations can be productive. These models are designed to adjust a training scenario according to individual progress, so trainees remain challenged and engaged every step of the way. These smart systems aim to provide an individualised learning experience that is adaptive in real-world situations, allowing for customised training and maximising the true potential of each trainee.

3. Time Management Types

Based on the requirements imposed on the simulator, it could be possible to model processes using continuous time, discrete events, or hybrid modes that combine both of them.

3.1. DES (Discrete Event Simulation)

A discrete-event simulation models the operation of a system as a discretely ordered sequence of events. Describes interval events in the system at a particular point in time. This technique can be applied and is very effective in the analysis of complex systems for optimisation and decision support, like those from the manufacturing industry, logistics management, or healthcare. DES allows for finding obstacles, improving efficiency, and predicting change by tracking statistics.

DES allows the simulator to speed up its execution, as only necessary time steps are processed.

3.2. Continuous Simulation

In continuous simulation models of systems, changes occur continuously over time instead of changing at discrete intervals. The examples for this mode of simulation are dynamic systems, such as simulations involving heat transfer or flight control. In the case of EAF, this continuous simulation can be used to understand the thermal dynamics and chemical reactions going on inside in order to improve temperature control as well as energy consumption.

3.3. Hybrid Simulation

Hybrid simulation is an integration of discrete-event and continuous simulation, to account for both the dynamic (discrete) behaviours with time-homogenous sequences as well as those involving physical characteristics over a period of time. In the case of EAF operations, a hybrid simulation might include the continuous process of smelting and refining steel with discrete events such as material charging or tapping, giving an overall model for operation.

4. Critical Methodologies and Techniques

In modern steelmaking, critical methodologies and techniques such as simulations using virtual reality (VR) and augmented reality (AR), agent-based simulation (ABS), and Monte Carlo simulation play pivotal roles. VR and AR provide immersive training environments for operators, ensuring safety and efficiency without real-world risks.

ABS models the interactions of autonomous agents to enhance system efficiency and safety, while intelligent agents simulate human roles to improve operational training. Monte Carlo simulations offer statistical insights by evaluating the impact of variable factors on emissions and product quality, ensuring robust and consistent steel production. These methodologies collectively enhance training, operational efficiency, and decision-making in the steel industry.

4.1. Simulations using VR (virtual reality) and AR (augmented reality)

This kind of virtual reality simulation is the most widely used form of training and education because it gives the users a taste of scenarios that cannot be recreated or would otherwise cause's danger in real life. VR can also simulate the entire EAF operation for training operators, allowing trainees to practice complex tasks and emergency procedures without risk of harm while learning via VR. This is the simulation employed for operator and employee training.

4.2. Agent-Based Simulation (ABS)

Agent-based simulation is a way of modelling the interactions of autonomous agents (both individual and collective entities such as organisations or groups) with a view to assessing their effects on the system as a whole. For example, in the EAF environment, ABS might be used to represent how various operators and automated systems coordinately function together (or do not), providing insights into consequential impacts on aggregate efficiency or safety.

Another important technique of ABS is intelligent agents (IA)**.** IAs are autonomous entities (e.g., virtual persons, autonomous vehicles, or other systems) that are capable of understanding the surrounding environment and its changes, reacting to one another, and performing assigned tasks independently from the user. For instance, IAs could be used to play the role of on-site operators and other staff who is working in or near the casting area.

4.3. Monte Carlo simulation

Monte Carlo simulation is a method for acquiring numerical solutions to complex problems in physics, applied mathematics, and operations research that relies on randomness. The idea behind this method is to use information about the system and relevant statistics to perform multiple runs (replications) of the model and consequently evaluate the outcomes. For example, it could be used to perform numerous replications to estimate confidence bands for some values. Monte Carlo simulation could be applied to EAF operations, for example, by simulating how variations in raw material quality and energy supply affect the robustness or consistency of emissions and final product quality.

5. Verification, Validation, and Testing

The most critical part of this simulation development, which distinguishes it from simple games, is the verification and validation of the models. Indeed, the aim of the simulation is to reproduce the behaviour of a system or process with a certain level of fidelity; hence, it is necessary that the simulator's capabilities are sufficient for its purpose. For example, if the simulator is created with the goal of modelling thermodynamic and chemical processes inside the EAF in order to estimate power consumption, then these two models need to be checked by experts and compared with the real furnace, e.g., by performing field tests, in order to ensure that the outputs of the models are sufficient to achieve the overall goal.

According to the main thesis target, virtual reality (VR) is a valuable tool in training operators for the EAF operation cycle. This technology can replace an analogue furnace or smelter with additional learning opportunities for handling complex tasks and emergency situations that otherwise would involve serious risk in the real system. The immersive training approach improves operator competence, safety perception, and decision-making, resulting in a more efficient and safe EAF operation. Simulating through VR is a great step to ensure that operators are fully equipped and know the challenges of EAF processes, hence leading to high productivity rates with low operational risks. Virtual reality (VR) simulation is the major form of operator or employee training in such industries.

6. What Can We Simulate?

Virtual Reality VR is a technology that has been modifying the way training can be carried out in various industries by delivering an immersive and interactive environment to learn or acquire skills. The most attractive cases for the use of VR are those in which real-world training is difficult, expensive, or risky to carry out.

6.1. Manufacturing Systems

Simulation is fundamental in manufacturing operations. Its domain includes many aspects of discrete and batch manufacturing processes, flexible manufacturing systems (FMS), material handling systems, robotic cells, and automated storage and retrieval systems. They assist in the planning, optimisation, and control of manufacturing operations.

For example, Flexible Manufacturing Systems (FMS) simulation can be used to do so by: coordinating multiple controllers; using detailed process plans for task management; and predicting future system behaviour. Manufacturing VR training can simulate intricate assembly processes and machinery operations to prepare workers in a safe environment.

6.2. Inventory and Warehouse Management:

Logistics training in warehouse environments can also benefit from simulation. It involves controlling autonomous mobile robots within a virtual warehouse to conduct inspection tasks with on-board cameras. The simulation environment lets operators practice managing resources in a safe, controlled situation.

For instance, in a virtual warehouse scenario, simulating the navigation of mobile robots can lead to inspection and resource control optimization. According to the army, VR training can replicate actual logistics scenarios, allowing operators to improve their abilities without any risks in real life.

6.3. Cold chain management

Refrigerated environments are another added risk, and VR can offer warehouse staff the best possible in-depth training. Cold chain management simulations can aid in optimal warehouse operations for temperature-sensitive products. This includes refrigerated warehousing design and operation, storage process optimisation, and refrigeration transportation route planning to reduce energy consumption and avoid product loss.

6.4. Thermal Processes

Simulations emulate heat treatment behaviours in different applications, like machining and manufacturing. These models simulate hot spots caused during the cutting and turning processes and their impact on tool life as well as the workpiece material properties. Optimal setting of cutting parameters to avoid excessive tool wear and surface temperature, increasing the specific material removal rate as well as the final quality of the machined component.

Thermal process simulations will lead to machining tool life optimisation and increased efficiency. Virtual reality can simulate machining surroundings, which makes it viable for operators to educate themselves on the use of this tool.

Simulating real-world physics in materials science, like phase change thermal control and energy storage devices, is essential for a wide array of applications, from spacecraft power systems to loop heat pipes. The simulations provide insights into the thermal management systems applied in numerous industrial and scientific applications. Engineers can be trained to assemble and maintain these systems in a virtual setting with the use of VR.

6.5. Fluid dynamic

Fluid and gas simulation using fluid dynamics for simulating fluid behaviour helps optimise gas distribution in industrial plants. Since VR can replicate the conditions of the plant, this makes it easier for operators to both visualise and predict work-learning how gases behave.

CFD can be used to predict flow fields in ventilation systems (providing comfort air quality and temperature control), or it could determine the effect of emissions on the environment throughout city regions.

In conclusion, one vital aspect of using virtual reality (VR) has become the perfect training solution for a host of operators within electric arc furnaces. With a precise replica of the EAF operation in detail to simulate within an engineered virtual environment, trainees effectively manage demonstrated operationally demanding tasks and emergency situations without endangering themselves or working directly on the real furnace.

This training technique offers a more immersive, operator experience that can contribute towards enhancing safety standards and the better decision-making abilities of the EAF operators, ensuring efficient production with safer operations.

Using VR-based simulation, the industry can be certain that operators will know how to navigate the hurdles associated with their processes, resulting in higher productivity and lower operational risks

7. Simulation advantages

In this context, the advantages of a simulation in industrial training and operations are highlighted by a brief overview of how the process is quite straightforward and efficient in terms of operating the EAF cycle.

Low risk to systems and staff: Simulations, particularly those using virtual reality (VR), offer significant safety benefits. Training in a virtual environment means there's no danger of costly damage to actual machinery or equipment. VR eliminates the potential for accidents that could injure workers during training sessions, ensuring that personnel on site are not at risk.

Additionally, trainees can learn and practice complex procedures without the fear of personal injury, providing a safe and effective learning experience. These safety advantages make VR simulations an invaluable tool for industrial training, enhancing both efficiency and safety in operating the EAF cycle.

Cost effectiveness: Running simulations are way cheaper compared to physical trials. For EAF, setting up physical training is expensive and may require significant resources and equipment, VR allows the entire furnace operation to be replicated with no risk.

This cuts down on the physical challenges required with less deterioration due to the use of real equipment. It can also optimise resources by practicing different configurations, and finding the best and most economically viable cycle of casting before production begins.

For instance, human operators can safely test alternative charging and tapping methods at an electric arc furnace. This ensures the best usage of resources and saves operational costs by stopping the running of faulty pipelines. Simulations identify the best configuration for operation parameters and scheduling, so that the furnace can be operated more efficiently, decreasing waste and downtime.

Enhanced Visualisation and Comprehension: Simulations to understand the behaviour of complex systems help operators better manipulate parameters and try new alloy compositions or energy sources in a simulated EAF. You need this feature when you want to troubleshoot or design systems with different chemical formulations. Simulation enables a better understanding of how operational parameters impact furnace performance for EAF operators, so they can make more informed decisions.

Increased Motivation: VR training could increase the motivation of trainees to follow and try the simulation frequently. The level of engagement with VR keeps participants very focused, resulting in great learning outcomes, Enthusiasm goes through the roof. Through this immersive experience, operators become more involved in their training, which leads to a better understanding and retention of material.

Identification of problems and troubleshooting: Simulations allow for detailed examination of complex systems to help identify present issues. This capability proves to be extremely valuable in identifying problems and testing solutions without impacting actual operations. The simulations within EAF can recognise limitations and bottlenecks in the time delays of processes, which point to potential areas for innovation.

Simulation could be enabled to log every event and action performed by the user, which may be used for training analysis. For instance, it could help to evaluate actions performed by trainees in order to identify errors.

Decision-making improvement: Time is vital in certain industries, such as EAF operations. By utilising simulations, operators are prepared to make informed decisions and implement changes within seconds when confronted with obstacles. The flexibility of VR enables operators to have a deep view of how their operations are performed and where they can be optimised.

By simulating, it is possible to quantify the examination of different scenarios in order to make better decisions. This has the benefit of allowing you to test different setups and expected outcomes before deploying them for real, which can save a lot of money by avoiding costly mistakes as well as improve resource utilization. This is highly required for a fully informed decision-making system in EAF operations.

Limitations and Challenges of Using VR and Simulations for EAF Training: While training operators with virtual reality (VR) and simulation technologies has the potential to provide many benefits for this type of industrial operation, it also comes with limitations and disadvantages that we should be aware of in order to establish effective EAF operations training programmes.

Incorrect Simulations: If the simulations for an EAF do not accurately simulate its physical processes and activities, they can be misleading to trainees. Inaccuracies like false temperature controls, incorrect chemical reactions, or a misrepresentation of how an electrical system works may result in operators learning methodology incorrectly. As a result of this kind of exposure, the training the trainees end up practicing is insufficient and unsafe. Finally, it could lead to negative training.

Low-fidelity models: As a consequence of not representing the EAF operations with all the details or realism, lower-fidelity models might lose some important portions of the complex reality. Such simplified models tend to miss essential aspects like the slag pattern, leading to inadequate skill transfer and an inability for operators to handle complex situations effectively.

Old Data: Old or incorrect data may cause the trainees to mimic misleading and unsafe practices when doing simulations. Operators often end up using outdated procedures, which reduces performance and increases safety hazards.

8. Training with Serious Games (SG)

Serious Games (SG) primary objective is not just pure entertainment. They use mechanisms with gaming and influences for real-world problems. Games are used in many areas, such as education, health, the military, and corporate, to teach users by involving them in the game and improving their skills. Serious games utilise the engaging features of traditional games but have a higher purpose, which is educational objectives.

A high level of encouragement is one of the outcomes of this technology. They are fun and yet challenging learning styles that make the process of learning more enjoyable and productive. These games simulate everyday experiences and challenges, enabling the learners to solve complex problems or face several obstacles as if they were experiencing them in real life.

Furthermore, we are able to mimic complex machinery in an industrial training setting. A VR game targeting Electric Arc Furnace (EAF) operations, for example, might place trainees in a virtual foundry. Smarter practices and real-world tasks have stamina temperatures they can manage here alongside the material inputs. VR serious games have an impressive degree of interactivity and realism, which are significant factors in maintaining focus, attention, and motivation in learners so that the target skills can be learned in a very effective way.

The biggest advantage of this technology is that it can monitor learner progress and performance in real-time. In doing this, the data allow for real-time assessment; document low-spots and places where instruction must improve, and then tailor future training based on these results.

They represent a very innovative way to learn, much more engaging than traditional ways. Through the utilisation of cutting-edge technologies, they develop authentic simulations to improve both the learning experience and outcomes. Repetition in a virtual environment offers the opportunity for trainees to develop expertise where complex processes are understood and better problem-solving abilities can be honed.

It is projected that the application of serious games in training will increase along with technological influence. As VR and AR technologies further develop, these games will become more realistic and interactive, to the point where they can provide an even better training solution. On the whole, industries that choose to implement serious game-based binary learning over traditional training methods will expect remarkable workforce competence and elevated safety as well as productivity.

9. The effect of graphics

Graphics are essential for identifying issues, as they help interpret complex data and scenarios with clear visualisation and high detail. High-detail visualisations are used to identify issues as they tend to help envision situations in a clear way. These combined visual tools facilitate easy identification of any irregular event, such as different temperature zones or the settlement of material in EAF. Thanks to these highly graphically detailed figures, the trainee is able to see through the complex dynamics furnace, pointing out any potential issues.

Training simulations benefit especially from high-resolution graphics that approximate real-world scenes. For example, trainees will gain familiarity with how to detect and respond to serious issues like a sudden increase in temperature or small gas leaks in the virtual world. This tactile feedback, combined with the insights provided by visuals, ensures that trainees come to grips with what exactly their choices entail in a low-pressure environment.

For instance, in safety training, VR environments mirror hazardous conditions like chemical spills or equipment failures. These simulations teach trainees how to recognise and react properly to threats.

High-quality graphics could also provide another benefit. In particular, high fidelity video may enable the utilisation of Machin Vision systems inside the virtual simulation. This could help with the testing of new systems and the development of specifications.

10. Equipment and devices for VR

Virtual reality (VR) requires specific equipment and devices to create interactive experiences. The primary equipment includes computers, headsets, or even smartphones, each with its own distinct role and capabilities in VR applications, especially in industrial training contexts such as Electric Arc Furnace (EAF) operations.

10.1. Computers

High-performance computers are essential for running complex VR applications. They need to have robust processors, high-end graphics cards, and sufficient RAM to handle the demands of VR environments and ensure smooth operation without lag. VR-ready computers typically include specifications such as high-resolution displays, fast refresh rates, and multiple USB ports to connect VR peripherals.

In an EAF training setup, a high-performance computer is required to render detailed 3D environments and real-time simulations of furnace operations. This ensures that the training experience is seamless and immersive, providing realistic scenarios for operators to engage with.Computers are also used in developing VR applications. Software tools like Unity3D and Blender are run on powerful computers to create and optimise 3D models and game environments.

10.2. Headsets

VR headsets, or HMDs, are the most crucial hardware for experiencing VR. They provide stereoscopic 3D visuals and track head movements to create an immersive experience. Popular VR headsets include the Oculus Rift, HTC Vive, and Meta Quest 2. These devices offer varying levels of immersion, resolution, and interactivity.An EAF training module using the Meta Quest 2 can offer a fully immersive experience where trainees can interact with virtual controls, monitor furnace operations, and practice emergency procedures in a realistic virtual foundry.

10.3. Smartphones

Smartphones can be used for VR experiences through affordable headsets like Google Cardboard or Samsung Gear VR. While these setups offer limited immersion compared to dedicated VR headsets, they are useful for familiarising users with VR technology. These devices utilise the smartphone's display and sensors to provide a basic VR experience, making VR accessible to a wider audience without significant investment.

Smartphones are particularly useful in educational settings and for initial demonstrations of VR applications. They can help introduce the concepts of VR and its potential uses in a cost-effective manner. Although they do not offer the same level of interaction as dedicated VR headsets, smartphones are a practical tool for getting users accustomed to VR environments and basic navigation within them.

11. Digital twin

Digital twins represent a major breakthrough in industrial simulations, providing detailed virtual replicas of actual physical assets. These digital twins are used to analyse, monitor, and predict the behaviour of industrial systems with the aim of improving safety and operational efficiency. Essentially, a digital twin is an exact virtual replica of a physical object, environment, or system, enabling the testing and experimentation of systems that may not yet exist. This technology allows for strong design optimisation and operational planning by simulating intricate scenarios that assess how modifications would impact operations or function under new conditions, ultimately aiding in the creation of effective procedures.

The relationship between digital twins and virtual reality (VR) is one of complementarity. VR and simulation technologies typically work alongside digital twins to create an immersive environment where users can interact with the virtual model in real-time. This combination provides an incredibly detailed view of processes, leading to better theoretical models for managing industrial operations more adeptly. For instance, with digital twins, virtual prototyping enables engineers to test various configurations and operational models within a simulated environment. This approach saves the cost and time associated with physical prototyping, allowing for faster iterations and optimisations.

A practical use case involves engineers evaluating new refractory or cooling systems on a digital twin of an electric arc furnace (EAF). By testing these configurations in a virtual environment, they can select the best combination before physical implementation, leading to more efficient methods.

Digital twins also create scenarios for training operators in operating procedures, providing an advanced, risk-free environment that supports the testing of emergency procedures without real-world consequences. Operators can practice their responses to hazardous scenarios, such as furnace overpressure or electrical faults, in an interactive environment, honing their skills and readiness without exposure to actual risks.

12. Virtual reality case studies

This section presents case studies demonstrating the use of virtual reality (VR) in industrial training and operations. The case studies include BP's implementation of VR for safety training and Volkswagen's use of VR technology to enhance assembly line worker training.

BP (British Petroleum)

BP (British Petroleum) has incorporated virtual reality into the safety training programmes of its workforce since 2017 for better preparedness and competency. The training on VR included emergency evacuation procedures, equipment handling, and response actions. BP used VR headsets to develop realistic scenario training modules for oil-rig emergency responses, enabling trainees to experience high-risk situations in a safe setting. Training offered live feedback, and real-time metrics allowed operators to identify their shortcomings and rectify them right away.

The performance was impressive, with a 40% reduction in safety incidents and a 30% decrease in evacuation drill times. On test runs, operators showed greater confidence and improved competence in managing actual emergencies. VR's immersive quality helped operators understand and retain safety protocols better than traditional training methods like 2D or written materials. Safety means less risk to employees and a faster response in emergencies.

The case study of the project at BP shows how VR is ideally suited to creating operational readiness and safety, with clear savings. This comprehensive methodology is intended to ensure that industrial operations are carried out safely, quickly, and efficiently.

Volkswagen

The world's biggest car manufacturer, Volkswagen, started using virtual reality (VR) technology to better train its assembly line workers in 2019. The purpose of this exercise was to improve accuracy and productivity in the line created for producing cars. Volkswagen created training programmes that meant employees could learn how to put together complex components or use new equipment in a virtual reality setting. Offering interactive features and delivering live feedback on their performance, these VR simulations greatly improved the quality of training available.

Volkswagen teamed up with SenseGlove to add haptic gloves to its VR training modules. This allowed trainees to, for example, pick up virtual parts with their fingers or feel what happens when a part is dropped. Trainees could move things around, feel how something felt on their fingers, and even touch any implements they would be using, creating more muscle memory training.

Its attractive use result is a product of this VR training program. Volkswagen also said that it reduced preparation and administration work by 25% and errors on average by nearly 20% with regard to traditional methods of training. The study shows that workers trained using VR performed significantly better in the task of assembling parts, completing it more quickly and precisely than their counterparts. Moreover, thanks to VR training, which substantially cuts back on the lengthy learning curve associated with new hires, recruiting and allowing fresh faces into production lines is much faster.

Chapter 5:

Developing a New Cockpit Design for EAF Operations

1. Introduction

The main goal of this chapter is to implement a developed cockpit design for electric arc furnace (EAF) operations as well as train operators. The first part consists of developing a Graphic User Interface (GUI) to be produced with Python codes in which the main parameters, such as temperature, power, and/or carbon level, during some stages of an EAF cycle should be displayed. This interface helps the trainee test whether the furnace is working at its optimum and learn what the ideal values for best performance are. The second part includes designing a control panel layout for practice by trainees using basic features such as electrode handling and furnace tilting.

2. Control Room Design History for Steel-making Processes

The technology used for controlling a steel-making process has gone from an analogue system to the introduction of advanced digital systems that combine real-time data analytics.

2.1. Early Designs

The features of early steelmaking control rooms were analogue controls, manual switches, and limited automation. They relied heavily on physical gauges and direct visual inspections from operators to understand furnace conditions. This was a very skilled and experienced level of setup.

The major challenges with analogue control were the high operator dependency, which resulted in increased manual errors and provided limited visibility to data. Operators who lacked advanced data monitoring struggled to identify the right setup for the furnace operations. The absence of process data in real-time and the lack of automated controls made it impossible for the manufacturer to react quickly enough when melting conditions were not optimised, leading to inefficiencies and variability in the final product.

2.2. Evolution

A significant development in control rooms was when monitoring systems moved from analogue to computer-based structures. SCADA (Supervisory Control and Data Acquisition) systems were an innovation that made fast and efficient control possible in real-time.

SCADA systems, which became popular in the 1960s and saw significant advancements in the 1970s and 1980s, can process data on set points driving control outputs to start or stop equipment sequentially. It allows better visualisation of the processes in an operational manner once further systems are installed.

The evolution has greatly improved monitoring and control precision, along with sophisticated data visualisation options and the centralization of process control. This has resulted in a marked reduction of operator involvement and human errors, allowing for more uniform operations.

2.3. Modern Era

The human-machine interface (HMI) has transformed the control rooms to a great extent. These data analysis tools, together with better automation, transformed the way that operators interact with systems. Through larger touch screens, they give real-time data regarding the trusted aspects of your operations, which is increasingly and interactively intuitive.

All aspects of the process are continuously monitored and controlled via these monitoring systems through the integration of advanced sensors and measurement devices, which helps improve decision-making and operations efficiency.

The benefits of HMIs involve optimised operations, additional visualisation, better safety, and increased productivity. Using real-time data and sophisticated visualisation tools, operators can gain the immediate insights they need to proactively manage resources by making quick decisions based on their predictive knowledge of where things may not be going as planned. Automated alerts and advanced safety protocols allow deviations or hazards to be responded to quickly with very little potential for human error, creating more reliable process control.

The human-machine interface helps in effectively managing the complex parameters during electric arc furnace (EAF) operation. These HMIs are created to be multimodal, enabling operators to have a more natural and intuitive interaction with the system by offering them complete real-time perspective data about their system status.

In addition to making the operation much easier in the real world, non-obtrusive interfaces give us critical information and, at the same time, too many details, which helps the trainee confidently apply the changes when he faces an obstacle in the real world without getting confused and panicking.

Comprehensive training programmes are essential to equip operators with the skills needed to use the new interface effectively. Continuous feedback mechanisms should be established, allowing operators to report issues and suggest improvements, fostering the ongoing enhancement of the system.

3. The Control Rooms in EAF Operations

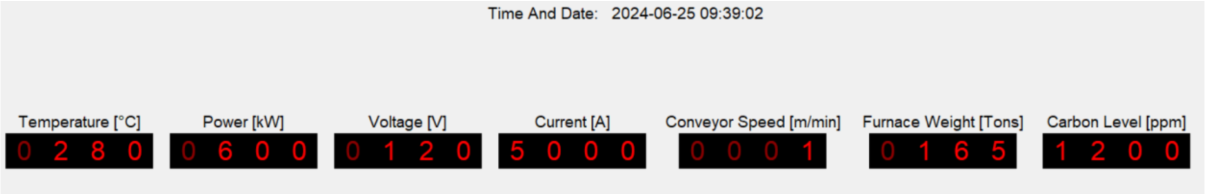
In Electric Arc Furnace (EAF) operations, control rooms can be thought of as the heart of the system, where operators oversee and fine-tune the processes occurring in the furnace. Efficient and safe operations are key to the design of these control rooms, or "cockpits." This section explores the key control room aspects of EAF operations, covering what is to be done, the information required, and the outcomes generated.

Casting management in EAF operations oversees the entire process of melting scrap metal, refining it, and casting it to a desired shape and composition. The furnace steel-making processes are designed to be carried out with fine control over a number of parameters, including correct operation to produce high-quality output. Good management of casting is a critical condition for achieving the most effective furnace performance and providing long-lasting, high-quality steel production with the minimum energy. Well-managed systems can eliminate operational downtime and avoid hazards that could lead to accidents like equipment overheating or incorrect chemical balance.

EAF operations must be watched at all times to confirm that everything works as it is supposed. The advanced sensors active for the furnace running collect real-time data on various aspects of operation, from temperature gradients to exact electrode positions, chemical reactions, voltage, and power, which are displayed on the real-time screens in the control room. Furthermore, operators should be sensitive about monitoring cameras in the cycle process to ensure the safety of the operation, either for workers or the equipment.

As we discussed before, the electric arc furnace (EAF) process consists of different stages like charging, melting, refining, and tapping operations. It is necessary to build a model of EAF to represent parameter values in indicators for the realisation of human-machine interface (MMI) to assist operators and process control. Here we concentrate on the input of the control panels, parameter monitoring, and why that matters at the cycle of the EAF by creating a GUI (Graphical User Interface) using Python codes.

The operation of the EAF depends on how well it is operated to maintain high efficiency and quality. In essence, they are required to monitor different factors at all times and adjust parameters in real-time throughout the EAF cycle. Having these parameters laid out on a control panel is done through the visualisation of data, which enables us to make the right decisions as quickly as possible.



Time And Date: 2024-06-25 09:39:02

Temperature [°C] 0 2 8 0
Power [kW] 0 6 0 0
Voltage [V] 0 1 2 0
Current [A] 5 0 0 0
Conveyor Speed [m/min] 0 0 0 1
Furnace Weight [Tons] 0 1 6 5
Carbon Level [ppm] 1 2 0 0

Figure 18. Input parameters indicators of virtual EAF control room.

4. Inputs (data)

To be effective, control rooms for EAF operations need a range of inputs to monitor and control the furnace processes. These inputs are collected by different sensors and monitoring systems that allow operators to have all the information they need in order to make informed choices and are displayed in indicators.

In this chapter, the inputs and outputs are considered from the point of view of the user or operator. The inputs are the data that arrives from the field, and the outputs are actions done by the operator.

Temperature: Temperature measurement is crucial to controlling the melting and chemical reactions in an electric arc furnace (EAF). The furnace has thermocouples and infrared sensors installed in various zones, providing temperature measurements in real time. Although thermal couples may be inserted in the furnace only from time to time, this limits the capability of having real-time data.

Located throughout the furnace, these sensors report temperature changes continuously. Operators need this data to modulate the power input and control the melting process so that metal is heated up just enough before it can be further processed.

The precise control of these inputs helps operators preserve perfect furnace performance, essential for the energy efficiency of steel production, while reducing operational downtimes. In real-world operations, temperature control should be managed with great care, showing the key role in obtaining desired results within EAF operations and highlighting the need for constant monitoring of temperature levels, which a human-machine interface (HMI) trainee can practice to gain sufficient skills for real-world operations.

Power: Keeping track of power is very necessary in order to control the energy consumption of EAF. As an example, the power input given by the control panel can be approximately 800 kW during the melting phase. Power levels should be measured to make sure the furnace runs properly and there is no waste of energy due to power leakage. Operators can use the HMI to train on varying power input, which contributes to greater energy efficiency and cost-saving performance.

Current: During the melting process, it is necessary to measure and maintain a stable electric arc. The operator must know the bad consequences of arc instability, which make melting less efficient as well as potentially harming the furnace. HMI screens will demonstrate to trainees the necessary current stability and how to modify voltage levels with power supplies for this.

Voltage: Voltage is another crucial parameter in EAF operations. This influences the arc control and fusing capacity of a machine. The range for the voltages is between 400 and 600 V during EAF operations to ensure optimal maintenance conditions and efficient use of energy. Ongoing training with the HMI is essential for operators to understand how, when, and why they should adjust voltage levels in order to keep optimal melting conditions efficient and safe.

Conveyor speed: The conveyor or consteel speed determines the flow at which materials are loaded onto the furnace. To maintain a continuous melting process, operators must control the conveyor speed so that it is consistent at an appropriate feed rate. Training done by the HMI helps operators develop knowledge on how to modify conveyor speed as per the operational requirements of the furnace, ensuring smooth and continuous operation.

Furnace weight: It shows the mass of melt in the furnace. Checking the furnace weight is also important to avoid excess or shortage of melted materials because such things could decrease the efficiency of the melting process. Operators use this data to set the charging process and keep furnaces in optimal conditions. Practice using the HMI to watch and adjust furnace weight, so working in real conditions is less stressful. An important limitation is that during the melting phase, it is possible to only have an estimation of the real weight of the material inside. This fact requires periodic alignment of the measured and actual weight, which needs to be done by the operator.

Carbon level: One of the most important parameters in refining is the carbon level. The level of carbon in the final product must be around 0.20–0.25% (2000-2500 ppm) to make good steel, so it must be properly monitored and controlled by operators. The output control of carbon levels is a key requirement for meeting actual standards and ensuring quality. Training the operators with HMI makes them realise how important it is to achieve the specified percentage of carbon.

This value could be sampled periodically, while in between it is possible to use estimations.

5. Outputs (Controls)

The control outputs available for furnace operators from the EAF operations control room to adjust the processes in furnaces will be different. In the multi-cloud world, these controls prevent problems, allowing operators to adjust furnace settings. The practice of using these controls as HMI systems helps operators perform the same in real-world operations.

As before, the inputs and outputs are considered from the point of view of the operator, so the output is an action done by the user that has an effect on the system.

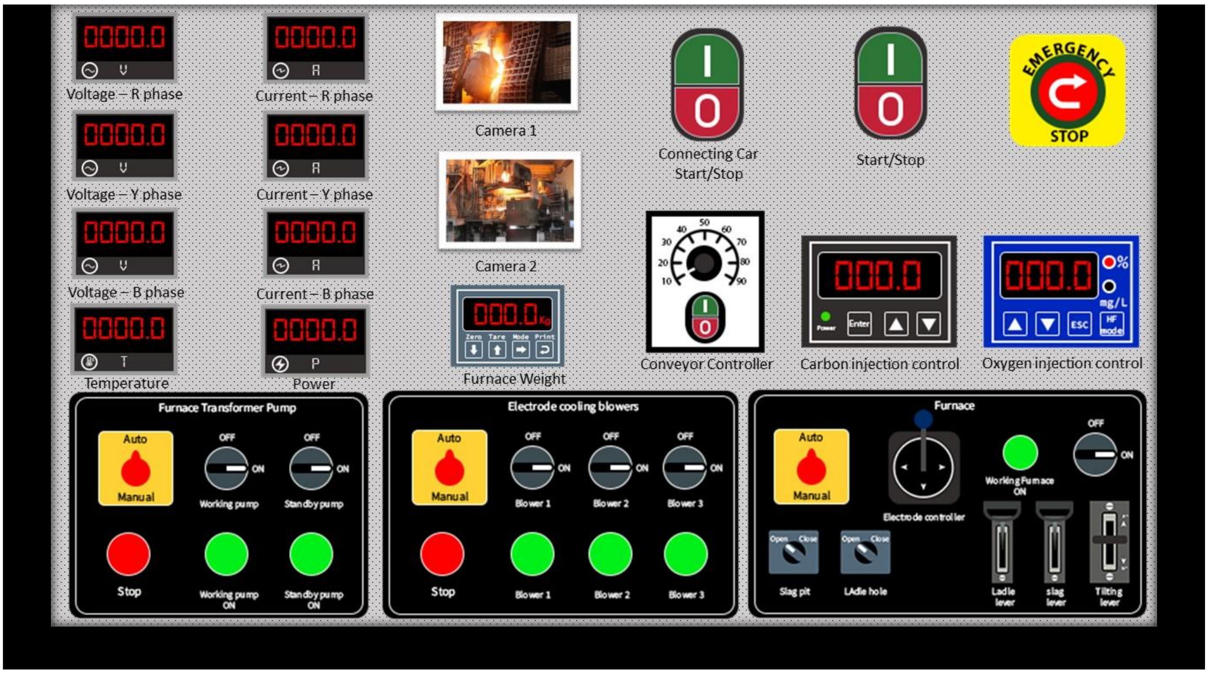


Figure 19. Virtual EAF control panel design.

Carbon injection control: Control of Carbon Injection into the Furnace Determines the proportion of carbon to be injected into the furnace. It is necessary to keep the molten metal with a reduced amount of carbon through the formation of slag, and this modifies the final quality of steel.

Operators can set their desired carbon levels through this control based on real-time measurement. Regular practice using this control would enable operators to understand the role of carbon balance in steelmaking and how precise variations in injected carbon can modify and deliver the required quality level of steel.

Oxygen injection control: To oxidise impurities like carbon, silicon, and phosphorous, oxygen injection is used to purify the molten metal. One of the most important functions is decarburization and temperature control.

Operators should tune the oxygen levels for optimal refining conditions, enabling successful impurity extraction at the proper temperature, among other things. Practicing with this control gives operators the chance to understand how manipulation of oxygen injection provides more effective refining.

Conveyor controller: The conveyor controller regulates the speed at which materials are fed into the furnace. Consistent feeding is vital for maintaining a steady melting process and ensuring energy efficiency.

Operators adjust the conveyor speed to match the furnace's operational needs. Training with this control helps operators understand how to maintain a consistent feed rate and the impact of feed speed on the melting process.

Connecting car start/stop: This control controls the moving connecting car, which carries materials to supply the furnace. This control needs to work as intended, or the timely and safe drop of materials will be delayed.

The operator must start and stop the connecting car in order to prevent excessive delays as well as ensure non-stop operation. Training on this control also teaches the operator how material is flowing, ultimately improving process efficiency.

Electrode Positioning Controller: The electrode positioning controller moves the electrodes to assist in creating the electric arc that is necessary for melting scrap metal. Effective arc-forming and stable molten conditions can be achieved using the correct position of electrodes.

Operators may move the electrodes to achieve precise arc lengths and stability. This guidance training teaches operators where to place the electrodes for optimum melting and minimal electrode wear.

Slag Lever Handle: A lever handle is part of the slag lever, which enables the removal of slag by tilting the furnace into an -8° position. The slag removal process is the key to your furnace lining protection and impurity elimination efficiency.

In order that the removal of slag can be adjusted well in the melting phase and refining stages, this method is used by operators. By training with this control, operators can learn how to deal with slag removal in order to protect the furnace and minimise impurity levels.

Ladle Lever Handle: It controls the pour of molten metal into the ladle using a lever and handle containing traces of lead by tilting the furnace into +5° or +6° positions. Careful control of this makes certain that molten metal is transported safely and efficiently to the next processing or casting steps.

The ladle lever handle is used by the operators to ensure that it is used adequately, maintain the optimum rate of pouring without splashing, and ensure the quality of the transferred metal.

Cooling blowers: Cooling blowers are used to cool the various components of a furnace in order to prevent overheating and ensure proper functioning. They work to keep the overall temperature balanced inside the furnace.

Cooling blowers are controlled by the operators to set the optimal the optimal temperatures of particular furnace parts for their condition. This training with the control teaches operators that cooling is key to avoiding equipment malfunctions and keeping operating temperatures safe.

Emergency Stop: The emergency stop button can cut off all operation of the furnace immediately in case of an accident. This is critical for safeguarding personnel and equipment from injury in the event that something goes wrong.

The operator must be trained to push the stop button very fast when there is an emergency problem. With regular training sessions, operators can understand when it is crucial to use the emergency stop button for quick response times and enhanced safety.

Furnace Transformer Pump: Furnace transformer pumps are used to regulate the coolant flow rate of furnace transformers. This is important because they need proper cooling to keep the furnace functioning and prevent overheating.

Operators use this control to regulate the flow of coolant, ensuring the transformer operates within safe temperature limits. This approach is a great way to train operators on the need for sustained cooling of transformers for reliable furnace operation.

6. Practical example

Now, let's see how the HMI can help operators better understand and manage the EAF process. In this example, the operation of a hypothetical EAF is analysed, which is inspired by real-world specifications but does not correspond to any specific model or facility.

Charging

Trainees load the furnace with scrap metal and other materials during the charging phase. From the control panel, he knows how much weight of what type is being charged, which should be around 100–150 tonnes of scrap metal. Precision measurement must be performed to get the exact input for melting, which impacts the steel output's efficiency and quality.

The furnace temperature must initially be kept at approximately 1,000 °C before the melting process begins to manage energy consumption more efficiently. There is 15% of molten metal in the furnace from the previous cycle, which helps keep the furnace temperature at the desired level, so the operator monitors the furnace weight and temperature to control the best optimum condition and prevent overloading.

Once the operator is sure everything is in order, he uses an electrode controller to detach the furnace roof to allow the addition of materials. At the same time, conveyor speed should be regulated accordingly (ideally 0.5–1 m/min) for consistent furnace loading, and the operator needs to find a way to control it effectively.

Melting

During melting, operators track input power, arc stability, and temperature. The power input to the furnace is, in general, 500–600 kWh per tonne of steel. This range in power ensures that energy is consumed efficiently while the target of having a stable melt process is achieved. Operators are able to utilise the Human-Machine Interface (HMI) to view real-time power consumption and make any modifications required in order for furnace operation to maintain this optimal power range.

Once the roof is attached, the operator should control and adjust the electrode positioning. Arc stability is very important for effective melting. Operators monitor the stability of the arc via the HMI, which helps him learn how to adjust it in real-time to keep the arc stable by monitoring the power level.

The furnace temperature under the melting phase is between 1600°C and 1800°C; therefore, operators would hold it quickly in this range to confirm the best possible condition is met. Real-time temperature data is relayed via the HMI, enabling operators to make tight changes in power input and arc settings to reach the desired temperatures.

Decarburization

During the decarburization step, the operator is required to monitor and control several key parameters in order to ensure the quality of the molten metal. There are some steps that must be taken for the production of steel of decent quality.

Additional overheating with oxygen lances ensures the purity of metal and carbon reduction, so first the operator monitors the carbon and temperature level of the furnace to make sure that materials are melted completely, then he can inject the oxygen lance by pushing its button in the HMI design. This further temperature increase forms a layer of slag with all the impurities at the top of the molten metal; furthermore, adding carbon can aid the formation of slag and decarburize the molten metal, so the operator can monitor the carbon level indicator and inject carbon whenever it is needed.

Tapping

During the tapping phase, sensors check both the temperature and chemistry of the liquid metal. Tapping temperatures will range from 1600 to 1654. When the liquid metal is ready, the first operator inserts the slag pit by pushing the slag lever handle and carefully tilting the furnace into the -8° position. After complete removal of slag, the furnace will tilt back to its vertical position to continue the tilting this time for pouring molten metal into the ladle. So first, the operator inserts the ladle, and then, by tilting the furnace into a 5° or +6° position, trains this operation. The last thing the operator should monitor and control is to keep the last 15% of residual molten metal for the next operation cycle.

Chapter 6:

New Training Procedures

1. Introduction

Proper training should concentrate on the essentials of EAF operation control, such as temperature management details, carbon balance precision, and their optimisation for energy performance. These training modules should include case studies and objectives so that the implementers are able to apply them in real-time implementations.

Learning to control temperatures is a basic lesson in operator training. Operators must also be aware of how to monitor, control, and adjust furnace temperatures so as not to cause de-carburization or carbon pick-up while maintaining the correct melting temperature in steelmaking. This also means understanding the importance of different temperature ranges and knowing what to do when there is a significant change in temperatures so that the furnace can perform at optimum levels.

Carbon management is the other key area. In addition, training must involve how to efficiently measure and correct the carbon levels in order to have suitable properties for the final steel products. It is done to ensure that the steel meets quality standards and that defects are minimised.

Furthermore, energy usage has to be considered because it has a direct relationship with cost and climate pollution, for which operators need to be trained to be able to operate in an energy-efficient condition, which includes knowing how to use data to make the right decisions on energy.

Controlling carbon levels: Carbon management is a critical area. Experiential learning should also cover how to accurately assess and control carbon levels to obtain high-quality steel. Carbon management helps to maintain the quality of steel and reduce defects.

The EAF process requires precise control of carbon content. Operators must be trained on when and how much to adjust the carbon injection rate using real-time performance feedback through chemical analyzers for molten steel-carbon analysis. So if a ladle of molten steel is cropped out with insufficient carbon content, the operator must immediately increase the injection rate and measure this additive until it reaches the desired quality.

Optimising energy consumption: The problem of energy consumption has a direct link to cost reduction and environmental sustainability. This involves training operators in the application of energy-efficient behaviour, which includes their skill to analyse the data and use technology to make the best decision in a short time.

For instance, if the melting cycle involves higher energy consumption than expected, power settings can be optimised by the operators in a way that does not affect the melt process itself. All of these solutions optimise energy and lead to a reduction in operational costs while making sure the facilities are running as effectively and efficiently as possible.

Emergency training is also important and should include emergency response directions, such as how to adjust levels or if it is necessary to shut down the furnace. Better training in emergency response also reduces equipment damage and mishaps.

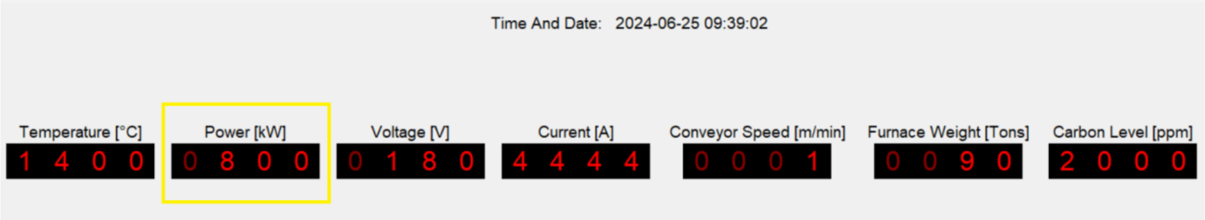
Detecting Anomalies and Malfunctions in Energy Consumption: Due to the diversity of energy inputs, operators are required to identify anomalous or malfunctioning conditions. Operators must have the capability to monitor energy usage for indications of abnormal operation that might signify inefficiencies or failures.

The operators need to be trained in such a way to understand the optimum energy usage in operation. Usually, these systems come with alarms that notify the operators whenever there is unusual energy usage. Anomaly detection practices must also be included in training so operators can spot patterns that suggest something is wrong, for example, if there's an unusual spike of energy during a certain phase of the melting process.

2. Example situations and expected outcomes

The aforementioned training procedures were developed to increase operator skills and promote high-performance-safety EAF operations. Operators experience these parameters in an industrial setting, managing the operational challenges and learning how to interpret them so that steel processes remain under control for a high level of quality production. The purpose is to equip the operators with a more comprehensive and similar experience of what they will have to do during real EAF operations in several scenarios. Here, some unexpected operational conditions are examined.

2.1. Unexpected power consumption during fusion



Time And Date: 2024-06-25 09:39:02

Temperature [°C]	Power [kW]	Voltage [V]	Current [A]	Conveyor Speed [m/min]	Furnace Weight [Tons]	Carbon Level [ppm]
1 4 0 0	0 8 0 0	0 1 8 0	4 4 4 4	0 0 0 1	0 0 9 0	2 0 0 0

Figure 20. Virtual EAF control room indicator-unexpected power.

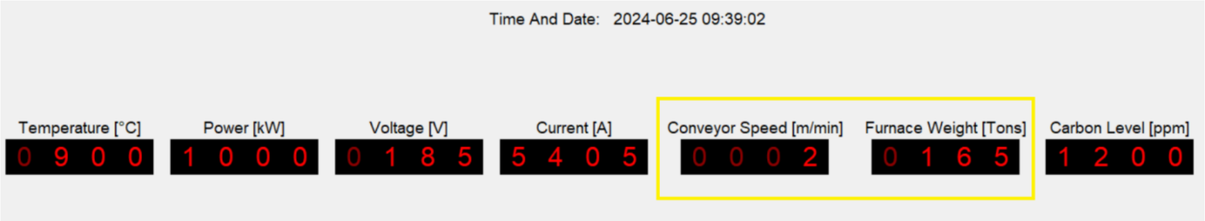
Unexpected power consumption can be a consequence of equipment failures or wrong operational settings due to incorrect electrode positions. The power consumption in the fusion phase should be between 500 and 600 kWh per tonne of steel produced, so power being consumed outside these limits shows inefficiencies in the system. The fluctuating energy consumption and irregular feeding rates result more or less from delays in operation, which is not desirable.

Increased power consumption has a number of different consequences. Firstly, it would increase operational costs because more electricity is being used. Second, it shortens the lifespan of major components and requires more frequent maintenance. Furthermore, melting temperatures can arise because of energy overconsumption, which deteriorates the steel quality due to variations in the chemical composition.

Operators need to make many interventions in order to solve these problems. The first decision is to modify process options, such as electrode positions, to stabilise the electric arc and decrease power consumption.

Furthermore, regular scheduled maintenance and calibration help avoid equipment failures that provoke higher energy consumption. Employing man-machine interfaces (HMIs) for monitoring in real-time enables operators to instantly act upon feedback on performance and ensure optimised operations as well to avoid these hazardous events in real-world operations.

2.2 Unbalanced mass



Time And Date: 2024-06-25 09:39:02

Temperature [°C]	Power [kW]	Voltage [V]	Current [A]	Conveyor Speed [m/min]	Furnace Weight [Tons]	Carbon Level [ppm]
0900	1000	0185	5405	0002	0165	1200

Figure 21. Virtual EAF control room indicator-unbalanced mass.

Based on the size of the furnace bath, the operator realises the charge of 180 tonnes is overloading, which occurred due to the wrong mass estimation or an unbalanced feeding rate due to the high conveyor speed. These errors arise from a lack of training, insufficient tools for measuring mass, or inappropriate computational methods to determine material volume.

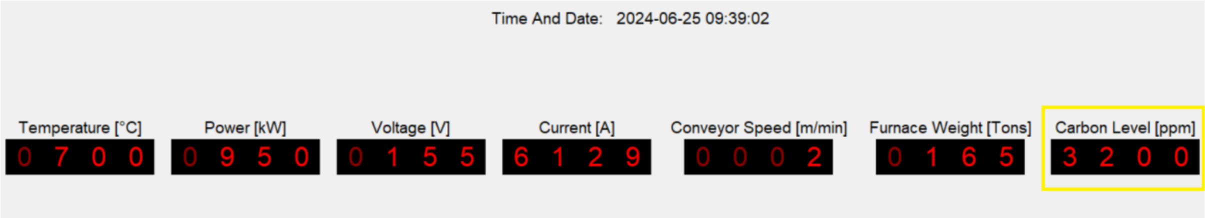
The consequences of this abnormal condition include increased power consumption of 1000 kWh per tonne of steel; instead, heating furnace temperature will reduce from its optimum condition in fusion to 900 °C, r resulting in low voltage conditions. These problems can cause increased costs to operate, damage equipment, and result in poor-quality steel. Additionally, safety risks due to possible machinery malfunctions may occur.

To overcome this issue, operators need to control the load rate by reducing the conveyor speed and remove extra scrap metal. If materials are melted, they can be removed by using tapholes;

otherwise, it creates another problem of blocking the taphole, so they need to stop the operation, overhaul the system, and remove the excess scrap.

Man-Machine Interface (MMI) training helps operators rapidly detect mass estimation errors, which can be critical. HMIs with simulation tools and real-time data analytic features help operators spot discrepancies in mass estimation far before they become problematic and adjust accordingly to keep the furnace running optimally. This training programme provides operators with the knowledge and understanding of utilising balances, flow metres, and computational tools for mass balance accuracy, which will result in efficient EAF operations.

2.3. Undesired carbon content



Time And Date: 2024-06-25 09:39:02

Temperature [°C]	Power [kW]	Voltage [V]	Current [A]	Conveyor Speed [m/min]	Furnace Weight [Tons]	Carbon Level [ppm]
0700	0950	0155	6129	0002	0165	3200

Figure 22. Virtual EAF control room undesired carbon content.

A higher carbon content in the furnace charge might be the result of many causes, including incorrect loading of scrap metals or operational mistakes and variations in material quality. For example, using the wrong quantities or types of scrap metal with a high carbon level or other wrong operations like electrode disposition.

Too much carbon makes steel have a higher hardness, but too high a hardness can make it rather brittle and prone to failure in structural applications. Inefficiencies like this tend to increase operational costs and increase the amount of maintenance required, which ultimately drops productivity, leading to a drop in profitability.

Operators have to take some corrective measures for this issue to achieve a more uniform melting process. The first thing to do is to insert the oxygen lance into the furnace to introduce more oxygen, which helps oxidise the excess carbon. Another possible solution is to add reagents such as lime (CaO) and other fluxes, which create a more reactive slag that binds with carbon.

Therefore, man-machine interface (MMI) training is very important at this point as it teaches the operators how to detect and correct mass estimate errors in a in a timely manner. Spreading this knowledge helps operators keep the plant under optimal conditions, leading to high-yield steel production with reduced risk of operation inefficiencies and defects.

The training of operators in the ability to control dropped temperatures, excess carbon, and energy consumption is an important part of electric arc furnace operations. Operators can improve EAF process control through thorough training that covers monitoring techniques, adjustment procedures, and emergency protocols. Realistic training scenarios and routine inspections help maintain the integrity of the furnaces and produce higher-quality steel at peak performance levels.

3. Emergencies and operator response protocol

Emergency preparedness is a critical part of maintaining EAF business, operations, personnel, and supporting the plant. One way to effectively train operators to respond correctly is by simulating a range of emergency situations and instructing them on the most appropriate responses.

Water Ingress: Once water enters the furnace, it carries a high risk of potential explosions. The melting process must be stopped by shutting down the power supply to the furnace immediately, which can only be done by the operator. Then, workers should engage the emergency water drainage system to pump out any remaining water from the furnace and immediately call the safety team for a site check-up.

Power Failure: If the emergency power supply fails during a melt, it will be impossible to manage critical furnace operations. It must use its integrated thermocouples and temperature sensors to observe the furnace temperature, keeping it below the defined safe threshold. Locating the electrodes and also configuring their power to manage heat and prevent any melting metal from solidifying is a very important process.

Adequate operator training leads to rapid restoration of electricity and the achievement of furnace stabilisation. It is crucial to keep the process continuously operating to effectively handle emergency power supply systems.

Overheating: If the furnace temperature rises above safe levels, the operator will generally reduce power by changing control settings on the furnace panel. The increased temperatures should be managed with cooling measures. It is essential to increase the flow rate of cooling water or air around the furnace shell while also monitoring temperature continuously to make sure the system comes back into a safe operating range.

Carbon Level Fluctuation: When the carbon levels are not within the optimum range, operators must use experimental instrumentation to find out how much carbon is in the steel. This requires the carbon injection system to be adjusted so that, in real time, only as much or little carbon is inputted into a reactor and allows for optimisation of oxygen injection and charging rates. By closely monitoring carbon levels, these concentrations would continue to stabilise in the permitted range and therefore maintain their qualities while ensuring that an appropriate carbon level is achieved.

Gas Leak: If a leakage of gas is detected, the operator must close all master valves and immediately evacuate the area to protect all personnel. The first thing to do is turn off the gas supply to your furnace, as continued leakage can be dangerous for workers, and activate the ventilation to get safely away from any trapped gas. To prevent this from happening, operators should follow the proper safety protocols quickly enough so that when these leaks occur, they can respond immediately.

Electrode Failure: If an electrode fails in operation, the operator is required to safely remove the electrode with suitable equipment for handling. In this case, workers should install a fresh electrode and ensure it is correctly aligned and connected, then resume usual operations while observing the performance of the new one.

Slag Overflow: If the slag level is above controlled limits, then the operator should start with the initiation of slag removal to reduce the overall molten slag in the system and prevent potential damage to equipment. This can be done by inserting the slag pit and carefully tilting the furnace to remove the excess slag.

Conclusion

In summary, our review of Electric Arc Furnace (EAF) technology demonstrates its critical role in modern steelmaking and highlights its environmental, economic and operational benefits. The EAF has been shown to be at the forefront of technological development, demonstrating superior environmental stability and operational economics.

As a result of legislative developments in many modern countries, older steelmaking facilities such as blast furnaces are no longer being built. Furthermore, the Climate Change Contribution of some of these industries is leading to their closure.

In light of these considerations, the operational performance of EAFs makes it essential, given the central role of the operator in such an industry. In addition to technological advances, there is a strong emphasis on the role of operator training in achieving the desired level of expertise, which can have a significant impact on the quality of the final product, as well as reducing material and energy consumption and, ultimately, costs.

As it is not feasible to have an expert operator at the start of their tenure. The traditional method of training new operators in real-world scenarios is employed for 100% of new operators. While this approach works, it does have its drawbacks due to concerns over safety, cost effectiveness and material and power consumption. To overcome this issue, new technologies are being developed to simulate the operation of complex and hazardous environments. We have developed a human-machine interface using Python code to simulate various conditions within the control panel.

It has been observed that an individual who has received basic training in BPMN files and an understanding of basic control management responsibilities and safety protocols can use this technology to engage in more authentic operational scenarios, thereby developing their ability to respond effectively to a range of situations. This process of experiential learning can enhance their professional competence and provide a sense of confidence in their ability to perform in a real-world environment.

Multiple scenarios can be tested by the trainees in a calm and tranquil environment which help them to concentrate on the problem, without getting involve into safety hazard and system malfunction.

References

1. Saboohi, Y., Fathi, A., Škrjanc, I., & Logar, V. (2019). Optimization of the Electric Arc Furnace Process. IEEE Transactions on Industrial Electronics, 66(10), 8030–8040.
2. Jerald, J. (2015). The VR Book: Human-Centered Design for Virtual Reality. Morgan & Claypool Publishers.
3. Matino, I., Colla, V., & Baragiola, S. (2016). Electric energy consumption and environmental impact in unconventional EAF steelmaking scenarios. In Proceedings of the 8th International Conference on Applied Energy (ICAE2016).
4. Sherman, W. R., & Craig, A. B. (2002). Understanding Virtual Reality: Interface, Application, and Design. USA: Morgan Kaufmann.
5. Karbowniczek, M. (2022). Electric Arc Furnace Steelmaking. Boca Raton, FL: CRC Press. DOI: 10.1201/9781003130949.
6. Macrosty, A. S., & Swartz, C. L. (2005). Dynamic modeling of an industrial electric arc furnace. Chemical Engineering Science, 60(13), 3555-3569.
7. Pangilinan, E., Lukas, S., & Mohan, V. (2019). Creating Augmented and Virtual Realities: Theory and Practice for Next-Generation Spatial Computing.
8. Aukstakalnis, S. (2016). Practical Augmented Reality: A Guide to the Technologies, Applications, and Human Factors for AR and VR (Usability). ISBN: 9780134094328
9. Modeling and Simulation of an Electric Arc Furnace Process. ISIJ International, 39, 23–32.
10. Klačková, I., Kuric, I., Zajačko, I., Tlach, V., & Wiecek, D. (2021). Virtual reality in Industry. IOP Conference Series: Materials Science and Engineering, 1199, 012005.
11. Proctor, D. M., et al. (2000). Physical and Chemical Characteristics of Blast Furnace, Basic Oxygen Furnace, and Electric Arc Furnace Steel Industry Slags. Environmental Science & Technology, 34(8), 1576-1582.
12. Cvetković, D. (2021). Virtual Reality. In Virtual Reality and Its Application in Education. IntechOpen. DOI: 10.5772/intechopen.91950
13. Bekker, J. G., Craig, I. K., & Pistorius, P. C. (1999). Modeling and Simulation of an Electric Arc Furnace Process. ISIJ International, 39(1), 23-32.
14. Santos, D. P., Santos, J. M. D., Portela, D. H., & Rodrigues, M. A. S. (2018). Operator training simulators in virtual reality environment for process operators: A review. International Journal of Interactive Design and Manufacturing (IJIDeM), 12, 1315-1324.
15. MacRosty, R. D. M., & Swartz, C. L. E. (2005). Dynamic Modeling of an Industrial Electric Arc Furnace. Industrial & Engineering Chemistry Research, 44(21), 8067–8083.
16. Bruzzone, A. G., Massei, M., Solis, A. O., Poggi, S., Bartolucci, C., & Capponi, L. D. A. (2013). Serious Games as Enablers for Training and Education on Operations on Ships and Off-Shore Platforms. In Proceedings of the 2013 Summer Computer Simulation Conference, 1-8.
17. Lee, B., & Sohn, I. (2014). Review of Innovative Energy Savings Technology for the Electric Arc Furnace. Metallurgical and Materials Transactions B, 45(4), 1103-1115.

18. Sekaran, A., Palaniswamy, M., & Balaraju, S. (2015). A Study on Suitability of EAF Oxidizing Slag in Concrete: An Eco-Friendly and Sustainable Replacement for Natural Coarse Aggregate. The Scientific World Journal, 2015, Article ID 972567
19. Bora, D., Masanori, S., & Toshihiro, T. (2010). Sulphide Capacity Prediction of Molten Slags by Using a Neural Network Approach. ISIJ International, 50(8), 1059–1063.
20. Chen, S., Wang, X., He, X., Wang, W., & Jiang, M. (2013). Industrial application of desulfurization using low basicity refining slag in tire cord steel. Journal of Iron and Steel Research International, 20(1), 26–33.
21. Moore, J. J. (2016). Chemical Metallurgy (2nd ed.). Oxford: Butterworth-Heinemann.
22. Chipman, J. (1951). Physical chemistry of liquid steel. In G. Derge (Ed.), Basic open hearth steel making (pp. 640–714).
23. Sato, M., Matsuno, H., & Ishii, K. (2017). Current Trends in Blast Furnace Ironmaking Technology. Journal of Iron and Steel Research International, 24(3), 227-234.
24. Machado, I. L., & Vilela, A. C. F. (2016). Ironmaking and steelmaking technologies as fundamentals for the steel production. 13(1), 35-40.
25. Yamashita, T., Nishio, S., Hara, S., & Kitagawa, K. (2001). Improvement in Blast Furnace Reaction Efficiency through the Use of Highly Reactive Calcium Rich Coke. ISIJ International, 41(10), 1234-1242.
26. Li, Y., Xu, Z., & Zhang, Y. (2023). Review on monitoring and prevention technologies of splashing induced by inappropriate slag foaming in BOF. ISIJ International.
27. Sanghvi, P. B., & Venkateswaran, R. (2012). Control of Slag Formation, Foaming, Slopping, and Chaos in BOF. Iron & Steel Review.
28. Kitagawa, T. (2011). Advances in steel refining technology and future prospects. Tetsu-to-Hagane, 97(5), 751-758.
29. Januszewski, J., & van der Aalst, W. M. P. (2018). Business Process Model and Notation (BPMN): A Guide to the Standard for Business Process Modeling. (pp. 11-22).
30. Ghosh, A., & Chatterjee, A. (2008). Ironmaking and Steelmaking: Theory and Practice. ISBN: 9788120332898.
31. Chatterjee, A. (2007). Principles of Steelmaking. PHI Learning Pvt. Ltd. ISBN: 9788120330122.
32. Duffy, V. G. (Ed.). (2020). Digital Human Modeling and Applications in Health, Safety, Ergonomics and Risk Management. Human Communication, Organization and Work Systems. Springer. ISBN: 978-3-030-49906-8.
33. Li, X., Yi, W., Chi, H. L., Wang, X., & Chan, A. P. C. (2018). A critical review of virtual and augmented reality (VR/AR) applications in construction safety. Safety Science, 105, 229-241.
34. Carter, G., & Smith, S. D. (2006). Hazard recognition and risk perception in construction. Journal of Construction Engineering and Management, 132(5), 512-519.
35. Radianti, J., Majchrzak, T. A., Fromm, J., & Wohlgenannt, I. (2020). Effectiveness of VR Head-Mounted Displays in Professional Training: A Systematic Review. Frontiers in Virtual Reality, 1, 563674.
36. Da Silva, J. R. (2009). Hot Metal Strategies for the EAF Industry (Report No. JB-09-001).

37. Nogues, Y. (2007). Introduction to Business Process Model and Notation (BPMN). (pp. 1-12).