BILAGA 3

Applications of thermal plasma torches for industrial furnaces: A review

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1 Introduction

1.1 Background

By 2045, Sweden is targeted to achieve zero net emissions of greenhouse gases into the atmosphere and should after that, achieve negative emissions. Negative emissions will mean that Sweden overall helps to reduce the number of greenhouse gases in the atmosphere. On the other hand, the steel industry is one of the highest CO_2-emitting sectors, accounting for 7% of CO_2 emissions globally. [1]. Energy consumption of the iron and steel industry in Sweden in 2016 was 21.7 TWh, in which fossil fuels account for about 16.9 TWh [2]. In the same year, Sweden's steel industry emitted 6.06 Mt CO_2-eq or accounted for 11% of Swedish CO_2 emissions [3]. The emissions of fossil carbon dioxide from the steel industry are mainly direct emissions from production processes (5.8 Mtonnes CO_2, 2016) and internal transport. These direct emissions are generated from the use of coal for iron ore reduction (85 %), the use of fuel to heat and process the steel (12 %) and from the coal content in raw materials and additives (3 %) [4]. A growing global population and expanding urbanization are expected to trigger a rise in global steel demand by 2050. Recycled scrap will not sufficiently meet the increasing demand for new steel [5]. The carbon footprint in the steel industry is thus a challenge for Europe and the rest of the world [5].

The electrification of heating furnaces in the process industries could have a crucial role in achieving Swedish zero net emissions target. The electrification of an economy coupled with greater supplies of low- to zero-carbon electricity sources can sharply reduce greenhouse gas emissions and has been a growing area of focus for technology research, development, demonstrations, and deployment (RDD&D) and supporting policies in many regions of the world [6]. The steel industry has adopted a climate roadmap to contribute to a fossil-free Sweden in 2045, where electrification is one of the keys to achieving high CO_2-savings [4]. To achieve significant CO_2 reduction, a new process called hydrogen-based direct reduction will replace the current blast furnace process. It is estimated that at the current level of production, an additional electricity demand of about 15 TWh has to be available, mainly for the electrolyser hydrogen production [4]. Further, for some processes where electrification is not feasible, the use of biofuels equivalent to at least 2-3 TWh is required as a substitute for fossil fuels [4]. However, there are high uncertainties considering the price, the supply, and the demand for biomass in other sectors [7].

The electrification of furnaces in the steel industry faces a big challenge as a significant portion of high-temperature heat is required to meet the operational need. These requirements are challenging to comply with conventional electrified heating (e.g., resistance and induction heating). Hence, the use of plasma torches as the route for electrification is gaining interest. The main advantages of plasma torches compared to other alternatives are the high temperature in the plasma jet, the high energy density of the plasma and the possibility to use different plasma gases depending on the desired application. Replacing fossil fuel burners with plasma torches can also lead to lower operating costs and greenhouse gas emissions. Other advantages include controlled process chemistry, small installation sizes and rapid start-up and shut-down features [8]. However, the main difference when introducing plasma torches is that there will be no combustion reaction in the firing zones, which changes the process gas composition and may include higher NO_x emission [8]. Hence, the application of thermal plasma for industrial furnaces should be considered carefully to achieve high efficiency and low emission level.

Furthermore, plasma technology may provide an alternative and complement to biomass. Interaction between plasma and biomass could possibly provide an increased flexibility and an extended life of existing furnaces. In some applications, the plasma technology has a potential to be combined with biogas. By developing plasma technology, the challenging furnace processes could possibly be fully or partially converted to electrified heating. This could provide the steel industry with cost-effective solutions and probably a faster conversion.

Considering the challenges above, the opportunities and limitations of plasma technology must be evaluated to judge its real potential. Further, a crucial issue is whether plasma technology can meet the requirements of the steel industry. Therefore, this report is written to provide information on the current use of plasma technology for industrial processes.

1.2 Methods

This report is based on literature studies. Used literature has been collected from various journal databases such as ScienceDirect (Elsevier Journals), Willey, Springers, etc. Available open access material found online has also been used in the prestudy. Furthermore, information regarding some plasma-related projects that are not available online was provided directly by the funding agencies (e.g. Energimyndigheten) or companies (e.g. ScanArc AB). Considering the aims of this literature review, most parts of the technological review are focused on the utilization of plasma torch to replace fossil fuel burner in the conventional heating furnaces.

2 Plasma technologies

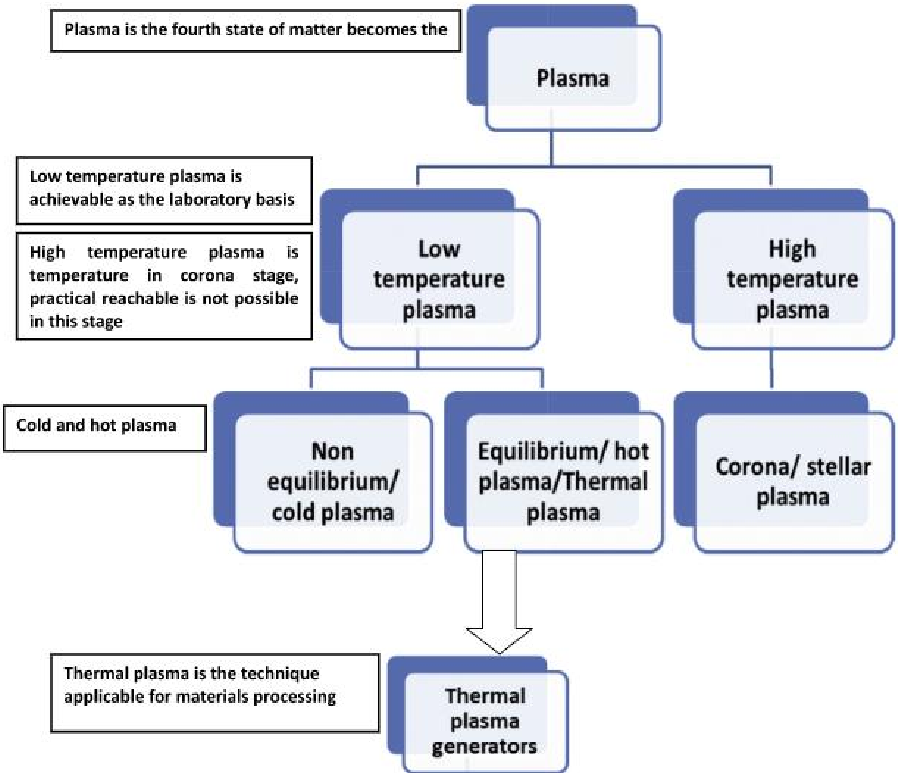


Fig. 1. Categories of plasma systems [9].

Plasmas are known as the fourth state of matter. A plasma is formed when sufficient energy is transferred to gas to ionize the molecules or atoms partially. The vast majority of the universe, including stars and the interstellar medium, is in the plasma state. On Earth, plasmas occur in lightning and flames; and are applied in many industrial processes [10]. **Fig. 1** shows the classification of plasma technologies as classified by Samal [9]. In general, the plasma technologies of industrial interest can be categorized as low-temperature plasma. On the other hand, high-temperature plasmas are not yet an industrial process as they are still in experimental devices aimed at producing nuclear fusion.

The plasma technology for industrial processes can be divided into two different systems which are cold plasma and thermal plasma. Cold plasma is characterized by low energy density and a large difference between electron and heavy particles [9]. Cold plasma technologies, such as in the food industry, normally work at a temperature lower than 100 °C [11]. In contrast, thermal plasma is produced at high pressure (>10 kPa) through direct current (DC), alternating current (AC), radio frequency (RF), or microwave sources with temperatures around 2000 - 20,000 K. The thermal or equilibrium plasmas are characterized by high energy density and equality between the temperature of heavy particles and electrons [9].

The general properties of thermal plasmas can be listed as follows [12],

- a high energy density and a high energy transfer rate,
- short reaction times for chemical reactions in the plasma, and
- a wide choice of plasma media as at high temperatures any materials can be plasma.

These properties make thermal plasmas suitable for a wide range of high-temperature industrial processes. Current use of plasma torch can be found in the areas of extractive metallurgy for recovery of metal values from slag, the smelting part in the process of metal alloying, processing of metal nanopowder formation, refractory and refining and destruction of waste materials [9]. The general requirements of the plasma torches are sufficient to power, the possibility of utilizing active gases and a long service life [9]. A single industrial plasma torch typically operates with power levels from 20 kW up to around 8 MW.

2.1 Formation of the plasma jet

Fig. 2 shows the illustration of a non-transferred DC plasma torch unit, which is one of the most common thermal plasma technology used for industrial processes. In general, plasmas are formed by supplying energy to a neutral gas, causing the formation of charge carriers. In this case, the energy is provided through electrical energy. Due to the externally supplied electric field, a conductive path for an electric arc is formed between the cathode and anode. The arc discharges provide a high density, a high-temperature region between the electrodes. With the aid of a sufficiently high gas flow that is introduced in the electrode gap, the plasma extends beyond one of the electrodes, thereby transporting the plasma energy to the reaction region. This part of the plasma is called the plasma jet. Common examples of plasma gases are Ar, N_2, He, air, H_2, CO_2, and steam.

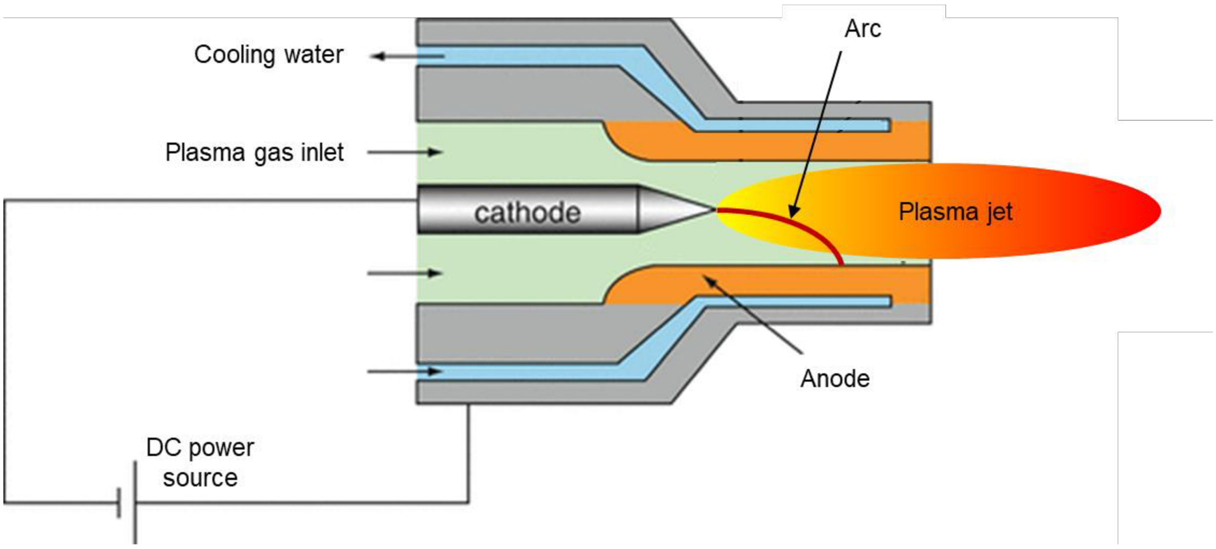


Fig. 2. Illustration of a non-transferred arc DC plasma torch.

2.2 Type of thermal plasma torches

In general, the main types of plasma torches currently used in the industrial process can be categorized based on their electrical discharge system, which are DC, AC, and RF. In contrast, the use of the microwave for generating plasma torches is still uncommon in the high power industrial processes. **Table 1** presents the summary of the characteristics of different plasma torches, while more explanation of each technology is available in this section.

Table 1. Characteristics of DC, AC, and RF plasma torches [12–17].

Type of discharge	Typical thermal efficiency	Pros	Cons
Direct current (DC)	70 – 90%	- The most widely used thermal plasma torch at industrial scales. - More options for the arc torch modes (i.e., transferred and non-transferred arc). - Less electrical disturbance and noise. - More prolonged and more stable arc operation. - Lower power consumption. - Lower refractory wear.	- Considerable erosion of electrodes, especially the cathode. - Extensive cooling is required to prolong the cathode life, which leads to considerable energy loss. - Additional cost and space are needed for the AC-to-DC rectifier. The power supply system can be 5 to 30% more expensive than that of AC plasma torches.
Alternating current (AC)	70– 95%	- The total service life is higher due to each electrode is an anode and a cathode alternately. - The power supply system is cheaper, more reliable, and easier to maintain than the DC plasma torches. - Possibility of combining multiple arcs in a large discharge chamber, which allows a higher power capacity for a single torch.	- Less stable arc compared to DC plasma torches. - More electrical noise.
Radio frequency (RF)	65 – 85%	- The plasma gas is not exposed to the electrodes, which allows the use of a wide range of gases, which include corrosive gases. - Ability to operate at atmospheric pressure, soft vacuum or even above atmospheric pressure up to 5 bar.	- Limited power (maximum 1 MW) - High investment cost - Lower thermal efficiency.

	- The plasma chamber has a high purity with no contamination from electrodes. Hence, it is suitable for specific industrial processes with a high level of purity, such as synthesis of nanopowders.	

2.2.1 Direct current (DC)

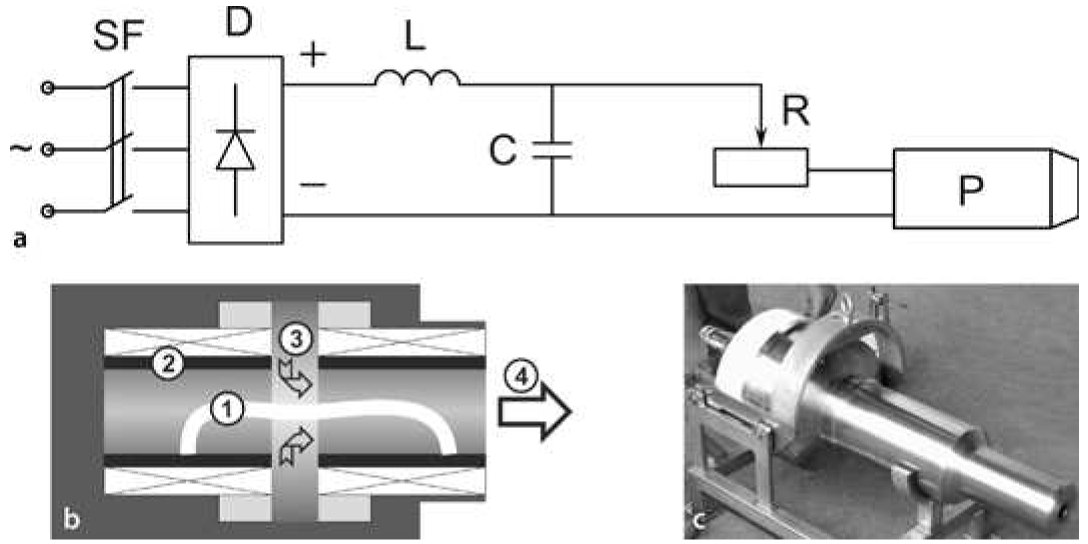
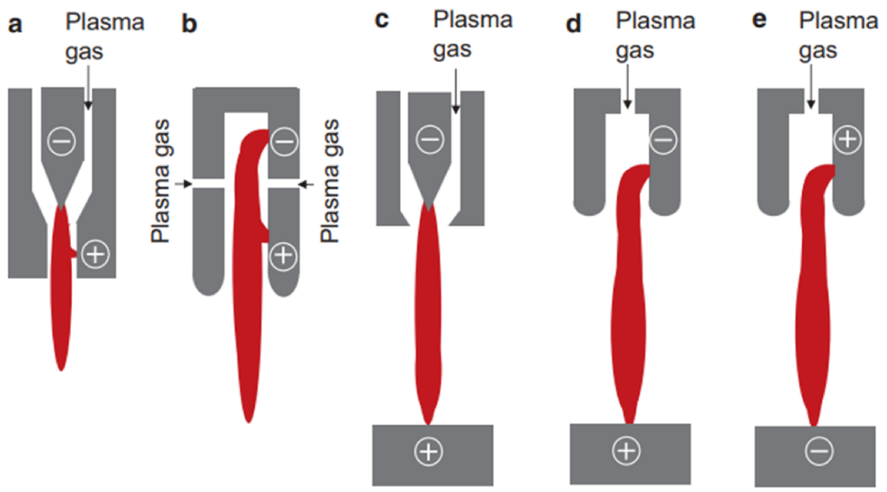


Fig. 3. a Typical power-supply schematic diagram of DC plasma torch (P plasma torch, D rectifier, L–C filter, R ballast resistor, SF automatic circuit breaker); b Schematic illustration of Westinghouse Plasma Corporation plasma torch (1 plasma column, 2 electrode, 3 entering plasma gas, 4 heated plasma gas); c Photo of 300 kW Europlasma's plasma torch [15].

DC plasma torches are the most commonly used plasma devices in material processing. In this application, DC electric currents up to 105 A is used between two electrodes which generate a potential difference in the input gas. The gas is then subjected to the confined space between the two electrodes, which supplies enough energy to initiate electrical breakdown, and leads to the plasma generation. The plasma extends beyond the anode in the form of high enthalpy and high-temperature plasma jet [12]. The typical power-supply system, as well as the schematic illustration of the DC plasma torch, are shown in **Fig. 3**.

DC plasma torches are known to have a significant drawback due to the presence of a sputtering phenomenon. In this phenomenon, the discharged atoms and ions from the plasma gas collide with the cathode surface, which leads to the release of the atoms the cathode and their deposition on the anode surface [12]. Consequently, the life-span of the electrodes decreases and extensive cooling of the electrodes is needed for stable arc operation. It is known that as high as 50% of the electrical energy supplied into the plasma torch is consumed by the cooling water, which leads to the low energy efficiency of the thermal plasma [12]. Nevertheless, it is essential to note the gradual shift of the plasma technology from AC to DC-based plasma devices due to the improved arc stability and the generally lower electrode erosion in DC plasmas compared to that of AC. This mainly results in the ability to optimize the choice of the electrode material to its polarity in DC sources, which is not possible in AC devices [14].

Furthermore, DC power supply technology has evolved considerably through the availability of high-power, fast switching thyristors, which makes most DC power supplies costing only 5–10 % more than comparable AC sources at the same power rating. It should be pointed out, however, because of the phase control strategy on the rectifiers, the arc voltage swings induce significant reactive power variations on the power network, and a static VAR compensator (SVC) or a static synchronous compensator (STATCOM) is always added to avoid flicker effect. Accordingly, the power grid disturbance with DC equipped with SVC and shift control is considerably lower than that of AC furnace (about 7 % of the power grid disturbance of AC furnaces) [14]. In a word, DC plasma torches are still favored in the industrial scale of material processing owing to the less flicker generation and noise, better control, more stable operation, lower consumption of electrode, lower power consumption, lower refractory wear, and a minimum two electrodes [12].



Configurations	Arc modes	Cathodes	Polarity
a	Non-transferred arc	Hot	-
b	Non-transferred arc	Cold	-
c	Transferred arc	Hot	Straight
d	Transferred arc	Cold	Straight
e	Transferred arc	Cold	Reverse

Fig. 4. Configurations of DC plasma torches commonly used for in a plasma generating device [14].

The design and performance of DC plasma sources have evolved considerably over the past five decades. As schematically represented in **Fig. 4**, a broad range of plasma torches and transferred arc furnaces were developed over this period depending on their ultimate use and the process needs. These can be grouped, based on the nature of the electrodes, into two broad categories: hot-cathode sources (**Fig. 4a and c**) and cold-cathode sources (**Fig. 4b, d, and e**). Alternately, they can also be grouped, based on the electrode configuration, into non-transferred arc sources (**Fig. 4a and b**) or transferred arc sources (**Fig. 4c, d, and e**). In the latter case, the configuration given in **Fig. 4c and d** can be recognized as being of a straight-polarity and (**Fig. 4e**) in "reverse-polarity" [14]. In the non-transferred arc system, both electrodes are incorporated in the generator, which requires high operating currents and has comparatively lower thermal efficiencies. This type of DC plasma is also used popularly for their high-temperature plasma arcs and better mixing of the plasma with reactants [12]. On the other hand, in the transferred arc configuration, one of the electrodes is the materials being subjected to the treatment, such as in the case of plasma arc melting furnace for metals. Hence, one of the electrodes, typically, the anode has a large separation distance to the cathode [12].

2.2.2 Alternating current (AC)

AC plasma torches are more promising for industrial applications and technologies requiring relatively high powers, even though it is not widely used. **Fig. 5** represents the typical schematic diagram of a power-supply circuit. The power supply system, in this case, is substantially cheaper and more reliable, rather than power-supply systems of DC plasma torches [15]. Their maintenance is also easier [15]. This contradicts with the technological complexity of the power supplies of the DC torches, which involves a high price, mainly due to the rectifier part of the electrical signal. Hence, AC power supplies could be an alternative for reducing costs. It is known that the use of AC plasma torches can involve a 30% lower price cost of the power supply [7].

In this technology, the gas is heated by the energy of an alternating current of industrial frequency. The physical processes of the burning of the arc at direct and alternating current are identical. The application of alternating current is associated with difficulties caused by the variability with the time of the electrical parameters of the power sources. The thermal efficiency of AC plasma torches is considerably high. In AC power-supply systems, the losses do not exceed several per cents as the reactive ballasts stabilizing an arc are used. Reactive power losses are minimized using standard capacitor compensators [15].

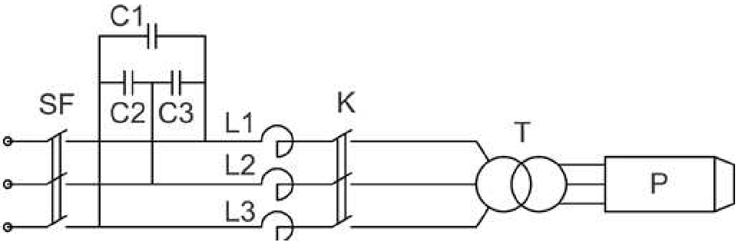


Fig. 5. Schematic diagram of a power-supply circuit of AC plasma torch (*P* plasma torch, *K* contactor, *T* standard step-up transformer, *L*1–*L*3 current limiting inductances, *C*1–*C*3 capacitor compensators, SF automatic circuit breaker) [15].

As classified by Rutberg et al. [15], existing AC plasma torches can be divided into three primary groups as follows,

- **Single-phase plasma torches.** In this basic configuration, a DC plasma torch with linear circuit and cylindrical electrodes is taken as a basis for single-phase AC plasma torches as seen in **Fig. 6**. The working gas is usually supplied tangentially into such a system. Another option of a single-phase plasma torch is a construction with the central rod electrode and ring or toroidal electrode. Usually, the arc is stabilized by the magnetic field rotating the arc in the inter-electrode gap. Such type of plasma torches uses an axial supply of the working gas.
- **Multi-phase with single-chamber plasma torches.** Their feature is the installation of an electrode system of the plasma torch in a single-electric arc chamber. The electrode systems of multiphase single-chamber plasma torches can have the form of rings, toruses, or rods. In the case of using toroidal or ring electrodes, generally, the first and the last electrode are connected to the same phase. Electrodes are usually separated from each other by heat-resistant insulating pads. **Fig. 7** shows some configurations of these plasma torches.
- **Multi-phase with multi-chamber plasma torches.** Multi-phase multi-chamber AC plasma torches comprise various combinations of several single-phase plasma torches using multi-phase AC electrical grid. Constructions are consisting of three separate single-phase plasma torches. It is possible to connect three single-phase plasma torches sharing one mixing chamber, while the connection configuration can be different. There is systems designed by this principle, for example, a multi-phase electric arc heating system.

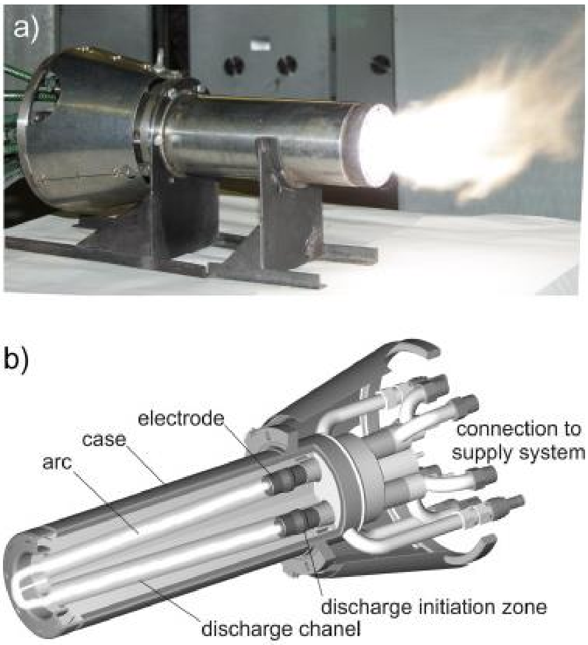


Fig. 6. The high voltage AC air plasma torch with rod electrodes: a – photo of operating at power 35 kW; b – schematic diagram [16].

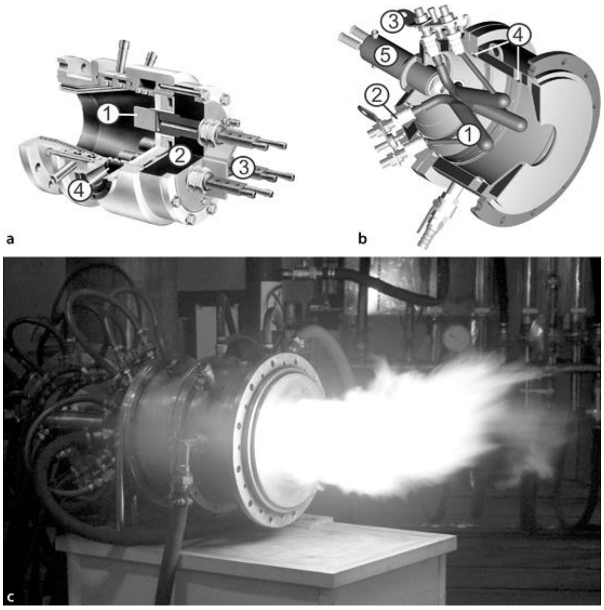


Fig. 7. Multi-phase with single-chamber plasma torches: a Three-phase plasma torch of EDP type (1 electrode tip, 2 insulator, 3 current lead, 4 gas supply loop); b Single-chamber three-phase plasma torch with rail electrodes (1 electrode tip, 2 insulator, 3 current lead, 4 gas supply, 5 injector); c Photo of operating plasma torch with rail electrodes, power 500 kW [15].

2.2.3 Radio frequency (RF)

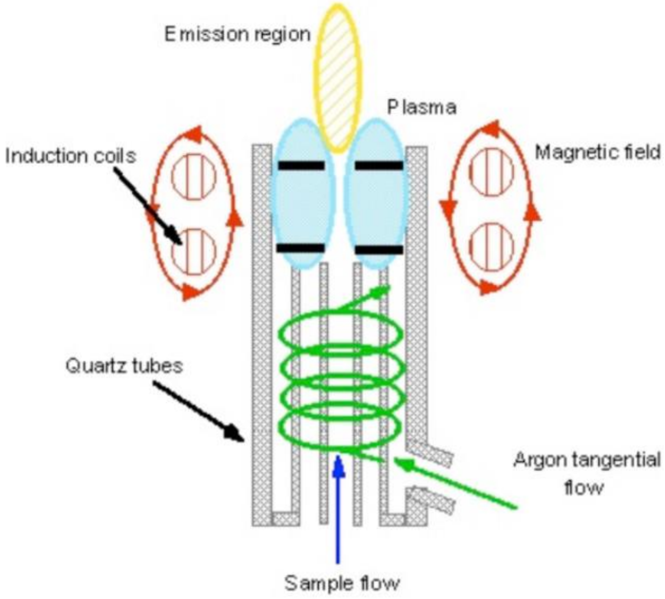


Fig. 8. Schematic diagram of RF inductively coupled discharge [9].

Almost all RF torches are inductively couple discharges, in which the discharge is sustained by the coupling of energy to the plasma through the electromagnetic field of the induction coil as can be seen in **Fig. 8**. The plasma gas does not come in contact with the electrodes, thus eliminating possible sources of contamination and allowing for the operation of such plasma torches with a wide range of gases, including inert, reducing, oxidizing, and other corrosive atmospheres. The excitation frequency is typically between 200 kHz and 40 MHz. Laboratory units run at power levels of the order of 30-50 kW, while large-scale industrial units have been tested at power levels up to 1 MW [12]. A typical design of a commercial RF induction plasma torch manufactured by Tekna Plasma Systems (Québec, Canada) is shown in **Fig. 9**.

Novel industrial-scale applications have been in development with varying degrees of success and industrial implementation such as [13],

- powder densification and spheronization, in which powders of various sources or chemical compositions are injected centrally into the discharge and melted in-flight forming high purity dense spherical particles with excellent powder flowability properties,
- plasma spraying, which involves the inflight melting of the feed powder in the plasma sources and deposition of the formed molten droplets on the substrate forming a coating or a near net shaped part, and
- plasma synthesis of nanopowders, which involves in this case the inflight heating, melting and vaporization of the feed material in the plasma source followed by the rapid quenching of the vapour cloud forming a very fine mist of nanopowders.

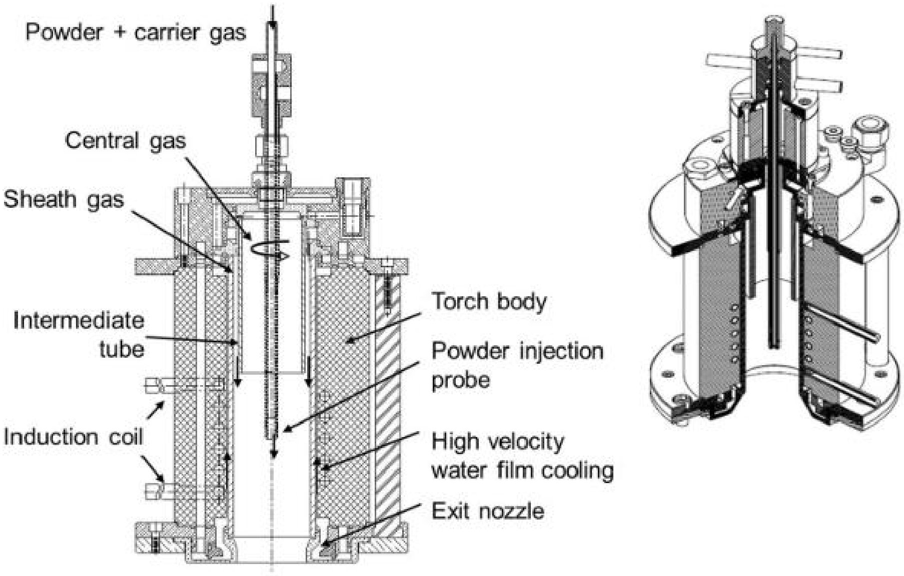


Fig. 9 Schematic diagram of a commercial RF induction plasma torch manufactured by Tekna Plasma Systems [13].

2.3 Effect of different plasma gases on the operation of furnaces

2.3.1 NO_X emission

The main difference when introducing plasma torches for industrial furnaces is that there will be no combustion reaction in the firing zones, which changes the gas composition inside the furnace. Secondly, there is an additional gas flow used to produce the hot plasma gas. This will slightly increase the flow rate of the heating gas and may also change its composition. More importantly, the temperature of the thermal plasma is significantly higher than the temperature of the burner flame. Higher temperatures could potentially lead to undesired effects, such as the production of thermal NO_x [8].

In general, the mechanisms of NO_X formation in an industrial furnace can be categorized as follows:

- *Thermal NO_X* – Mechanism responsible for increasing of NO in high temperature combustion. Thermal NO refers to the high temperature (above 1300 °C) reaction of nitrogen and oxygen from the combustion air.
- *Fuel NO_X* – Mechanism responsible for NO production when fuel has nitrogen included inside molecule (fuel bound nitrogen).
- *Prompt NO_X* – Mechanism responsible for NO production in the flame especially fuel-rich conditions due to high concentrations of radicals.

In a word, in a plasma heating process, potential of NOx formation will be occur mainly due to the following reasons,

- a higher temperature spot over 1300 °C and
- nitrogen presence owing to either from air leak or the use of air /nitrogen as plasma agent.

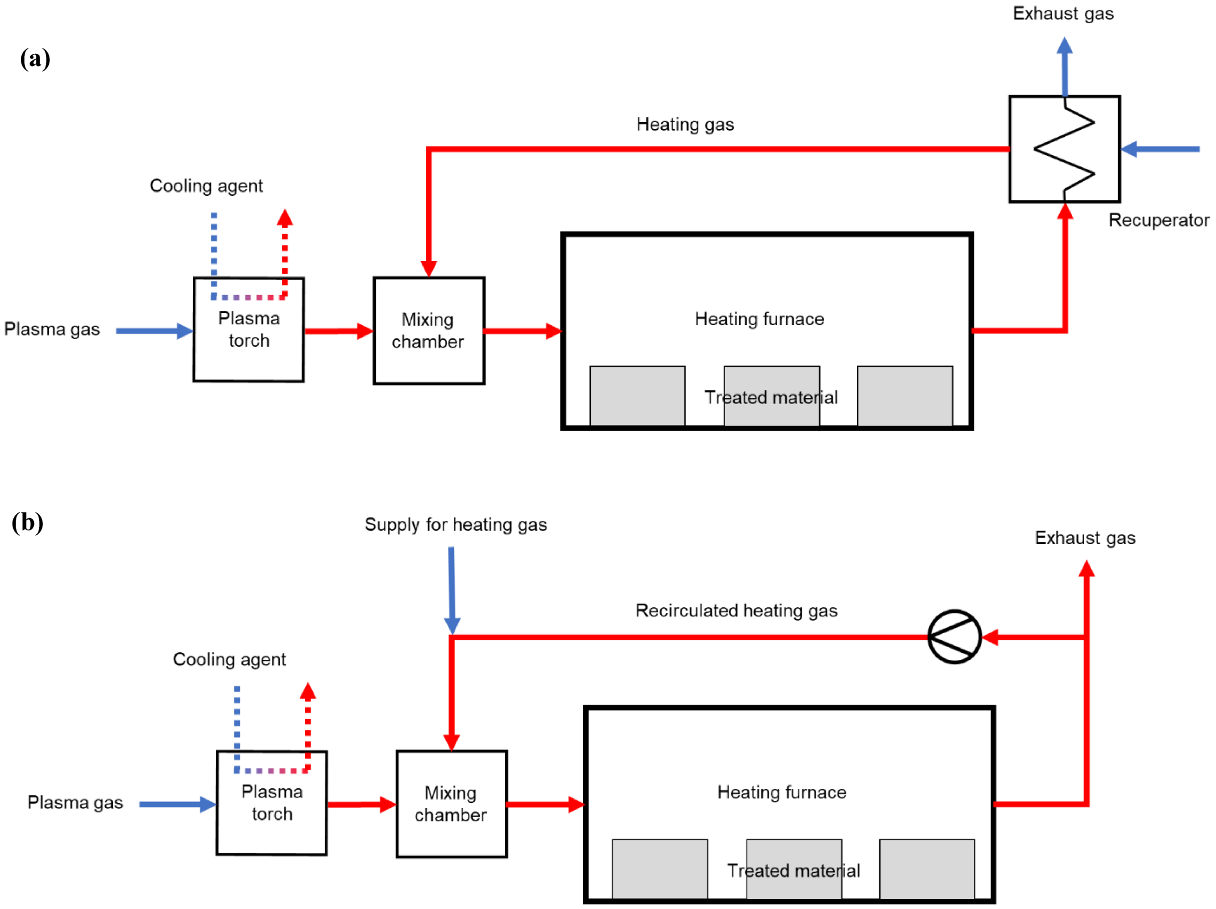


Fig. 10. Schematic diagram of the concept of a plasma-based heating furnace with (a) heat recuperations and (b) recirculation of heating gas**.**

In details, the NO_X emission in a plasma-based industrial furnace can be generated by two sources, which are the generation by the plasma gas itself and the generation due to the exposure of the hot plasma gas to the heating gas. Theoretically, NO_X can only be produced from the plasma gas if it contains both nitrogen and oxygen atoms as mentioned before. Hence, the production of NO_X is expected only in the case when air is used as the plasma gas. Other common plasma gases such as N_2, Ar, H_2 and CO_2 do not generate NO_X from the plasma. Nevertheless, NO_X can still be produced if air is used as the heating gas in the furnace. **Fig. 10** shows possible configurations of a plasma-based heating furnace. In these configurations, the energy from the outgoing heating gas can be recirculated back to the furnace through a heat recuperator or a direct recirculation of the heating gas. When there is air in the incoming heating gas, and it meets with the hot plasma gas in the mixing chamber, NO_X is then generated as the hot plasma gas accelerates the formation of thermal NO_X regardless of the type of plasma gas.

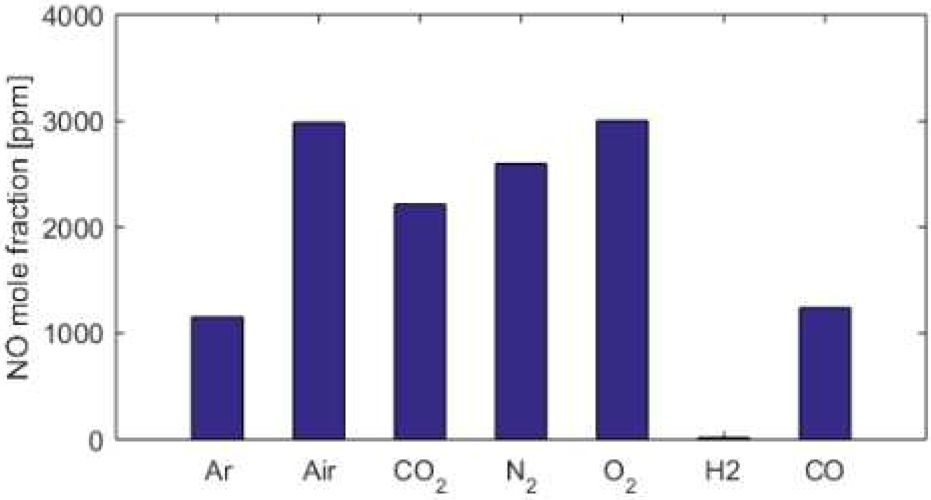


Fig. 11. NO mole fraction produced from different plasma gases [8].

Lindén and Thureborn [8] compared the generation of NO caused by different plasma gases during the heating process of iron ore pellet furnace. Through their simulation work, NO emission is calculated based on the assumption of air as the heating gas. As seen in Fel! Hittar inte referenskälla., the results obviously show that the use of air, N_2, or O_2 as a plasma gas will generate a high concentration of NO. Whereas hydrogen, argon and carbon monoxide are the gases that produce the least amounts of NO.

To summarize, the NOx generation in a plasma-heated furnace can be prevented by the following strategies,

- reduce the high temperature hot spots,
- avoid to use nitrogen or air as plasma gas or heating gas, and
- prevent any air leakage.

2.3.2 Lifetime of refractories

When it comes to the plasma utilization for industrial heating furnaces, the effects of certain gases on the lifetime of materials inside the furnace should be considered to choose appropriate plasma gases. This especially important when the furnace is operated at a high temperature. Unwise selection of plasma gases could cause excessive refractory wear which may cause a furnace to shut down. Depend on the type of refractories, plasma gases may cause different effects on their lifetime. Table 2 shows the classification of typical refractories used in the iron- and steel-making processes according to their chemical composition.

Table 2. Classification of refractories based on their chemical composition [18].

Chemical composition	Examples
Acid – which readily combines with bases	Silica, Semicilica, Aluminosilicate
Basic – consists mainly of metallic oxides that resist the action of bases	Magnesite, Chrome-magnesite, Magnesite-chromite, Dolomite
Neutral – does not combine with acids nor bases	Fireclay bricks, Chrome, Pure Alumina
Special	Carbon, Silica Carbide, Zirconia

Among common gases used for the plasma gas, steam is considered more reactive, which cause a higher oxidation rate for refractory and steel materials. Several studies have reported the effect of high-temperature steam on the oxidation of silicon carbide (SiC). Maeda et al. [19] examined the effect of different steam vapour concentration on the oxidation of SiC during heating at 1300 °C for 100 h. The results indicated that the weight gain by oxidation increased with increasing of steam concentration as the presence of steam strongly influence the oxidation of SiC and accelerated the reaction. It also found that the flexural strength of SiC was slightly degraded by the oxidation. Park et al. [20] investigated the oxidation of SiC in both air and water–vapour–rich environments at 1200 °C to examine the effects of different oxidation conditions on the early-stage oxidation behaviour of SiC. In contrast with the previous study, the results show that the samples oxidized in air showed weight gain during oxidation, whereas the samples oxidized in a steam environment showed a significant weight loss (active oxidation). This was also confirmed by the presence of pores only in specimens oxidized in steam. This contradiction may suggest the different oxidation effects between short and long exposure of SiC to the high temperature steam.

Nevertheless, when the refractory materials is Silica refractories (SiO_2 based), the effect of steam on the refractory materials is very small. According to Ovako, their experience in using oxyfuel combustions since 1994 shows that the lifetime of refractory is not affected by the degree of steam in the flue gas. Rather than the steam, the lifetime of refractory can be significantly reduced by the presence of alkali, high peak temperature, and sometimes most likely CO in the combination with alkali and high temperature.

2.3.3 Oxidation and scale formation of steel

It is important to note the use of certain reactive gases could also affect the quality of products such as in the case of steel slabs being treated in the heating furnace. The mechanisms for the high temperature oxidation of steel is shown in **Fig. 12**. The oxidation mechanism can depend on (i) the transport of oxidant gas from the bulk gas phase, (ii) phase boundary reaction(s) at the gas/scale interface, or (iii) the diffusion of Fe cations to the scale/gas phase interface.

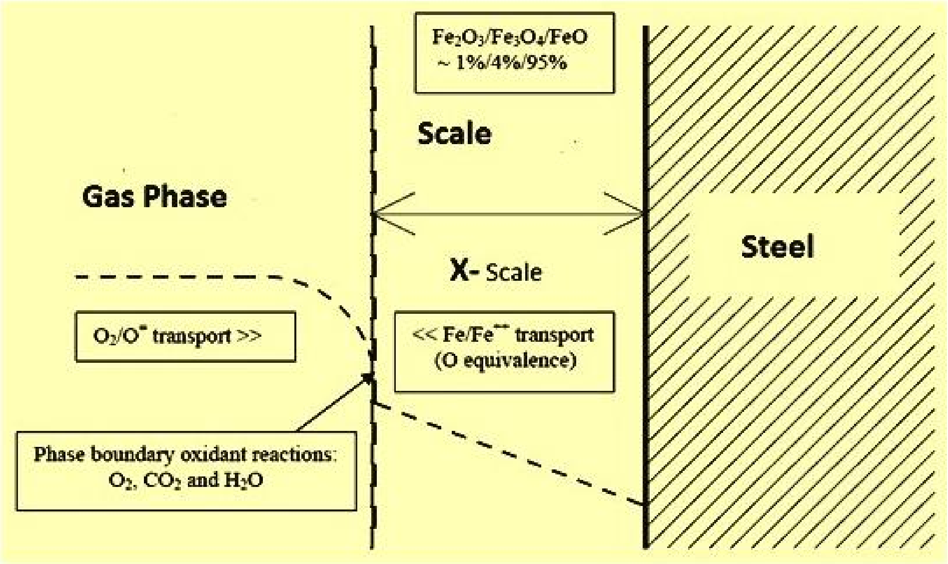


Fig. 12. Mechanisms of the high temperature oxidation of steel [21].

The rate of scale formation is known to depend on the partial pressure of oxidizers and steel surface temperature. CO_2, H_2O and O_2 are all oxidizing to steel when the surface temperature of the steel is above around 750 °C. For oxidation of different steels in CO_2 and H_2O atmospheres, CO_2 and H_2O may dissociate into O_2 and CO or H_2 on the oxide suface, which is stronger oxider for scale formation. In general, higher temperature results in a higher rate of scale formation. At lower temperatures than 900 °C, O_2 content has very little influence on oxidation of steel. However, at high temperatures (above 1150 °C), an increase of O_2 content in the furnace atmosphere from could increase the oxidation rate significantly [21]. Furthermore, the effect of water vapour and CO_2 on the oxidation of iron shows that the scale formation rate of iron is started to be influenced by water vapour at temperature above 850 °C. It is also known that CO_2 produces a smaller scale formation than water vapour [21].

The effect of a high-temperature steam atmosphere on the oxidation of different steels has been investigated by previous studies mainly through lab-scale experiments. Sobotka et al. [22] reported the behaviour of four steel grades during thermogravimetry analysis at 750 – 1200 °C under different steam concentrations (18.8 – 65.5 vol.%) representing the flue gas from oxygen-enriched combustions. The investigated steel alloys include low alloy mild steel, Cr-Mo steel, Cr-Ni-Mn steel, and Fe-Cr-Al steel. The study found that the oxidation rate starts to increase significantly at a temperature above 1050 °C during 100% oxygen combustion (corresponding to steam concentration of 65.5 vol.%), which leads to a significant mass gain as can be seen in **Fig. 13**. However, this phenomenon is not found in the case of low steam concentrations.

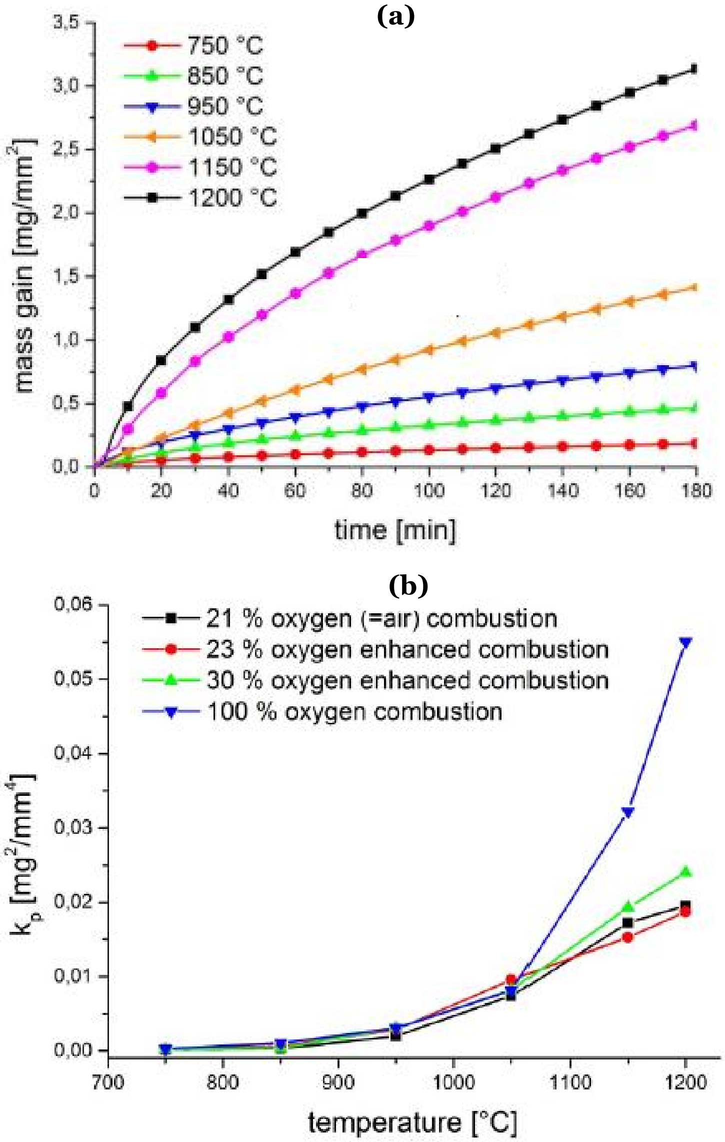


Fig. 13. (a) Oxidation rate of the alloy 42CrMo4 under 100% oxyfuel combustion, and (b) influence of the combustion atmosphere on the rate constant for the oxidation from 750-1200 °C of the mild steel [22].

Application of thermal plasma technologies

3.1 Iron- and steel-making

In general, the developments of thermal plasma in the iron- and steel-making processes are focused on the improvement of conventional technologies and the development of novel plasma technologies. According to the scope of its application in the iron- and steel-making (as seen in **Fig. 14**), the utilization of thermal plasma torches will be explained according to the following process: (1) Pretreatment of raw materials, (2) iron-making, (3) steel-making, and (4) steel heat treatment. Some of the plasma torch projects related to those processes are based in Sweden, as summarized in **Table 7.**

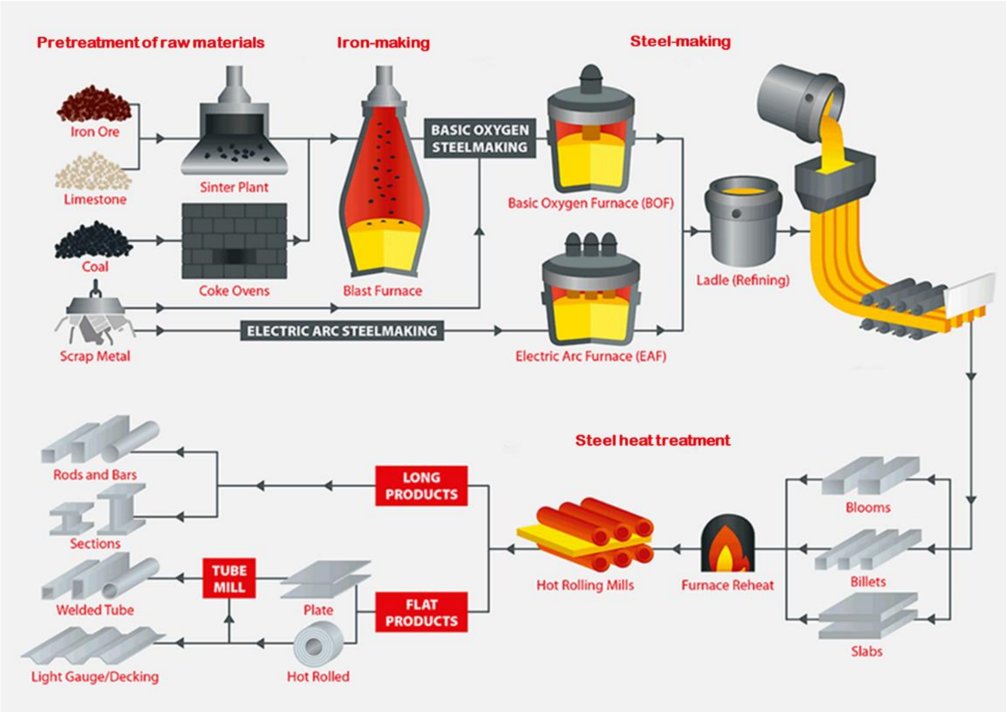


Fig. 14. Iron and steel making process [23].

3.1.1 Pretreatment of raw materials

The development of plasma torch to supply heat for pretreatment of raw materials used in the iron-making process is currently only focused on the iron ore induration process. Specifically, so far, only the project initiated by LKAB (Sweden) is found to develop this application. This project is a crucial component of HYBRIT, a joint initiative of LKAB, SSAB and Vattenfall. In the plant, fossil fuels will be replaced to achieve fossil-free production of iron ore pellets. The aim of the HYBRIT initiative, which is supported by the Swedish Energy Agency, is to develop a process for fossil-free steelmaking by 2035 [24]. **Fig. 15** presents a possible integration between plasma-based iron ore induration and the direct reduction of iron (DRI) by hydrogen.

The project was started by a simulation assessment of the novel plasma-based iron ore furnace through the collaboration project between LKAB and Chalmers University of Technology. The result of the assessment is reported by the study of Lindén and Thureborn [8]. The study focused on process simulation work to evaluate how process conditions are affected when an electric heat source is used to replace fossil fuels. A simulation model was developed to assess the process performance in term of product quality, energy efficiency, emissions of CO_2 and NO_x. **Fig. 16** shows the configuration of the plasma-heated straight-grate process that is considered in the study.

It is stated that direct exposure to the radiation from the burner flames should be avoided since it can cause overheating of the top pellet layers. Hence, the burners are placed in separate enclosures which protect the bed from most of the radiation [8].

Overall, the results of the study indicated that retrofitting plasma torches in place of fossil fuel burners in a pelletizing plant shows a promising potential with the following benefit [8],

- with a 40 MW thermal input has the potential to reduce CO_2 emissions by up to 140 000 ton per year
- the use of plasma torches in the straight-grate process only causes a small effect on the process parameters and energy consumption, and
- higher efficiencies in the pellet drying zone due to the absence of moisture content which is typically produced in the normal gas-burner.

On the other hand, the main disadvantages of using plasma torches can be summarized as follows [8],

- there are not any combustion reactions, and thus no combustion products in the process gas, which causes slightly higher content of oxygen in the gas and results in a higher oxidation rate of the pellets,
- significant amounts of NO is produced when hot plasma gas mixes with air due to the thermal NO mechanism, which increases exponentially with temperature. Reburning is the most promising reduction strategies, with NO reduction of up to 65 % in the simulations.

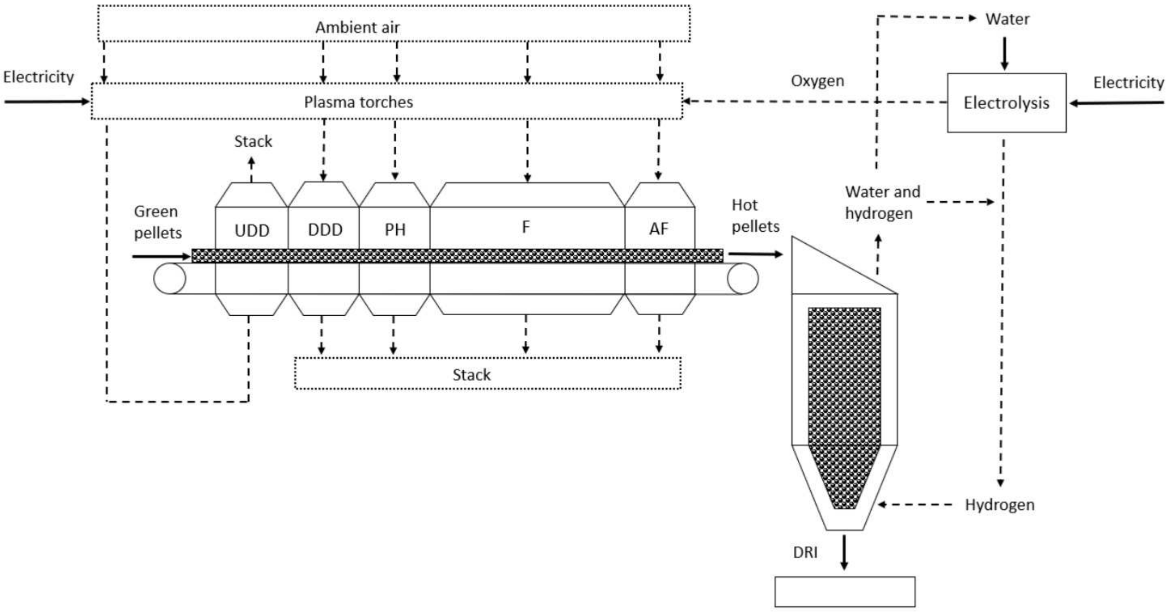


Fig. 15. The proposed new integration concept of a plasma-heated straight-grate furnace with a hydrogen-based direct reduction furnace [8].

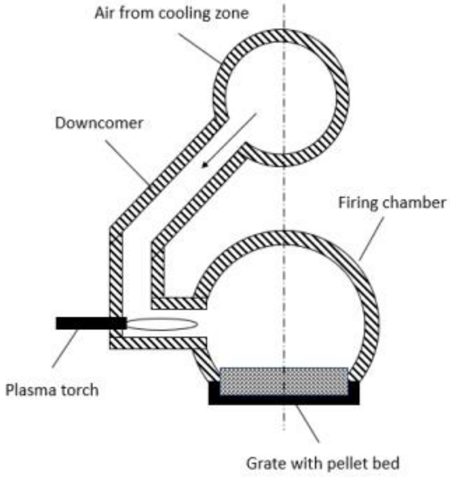


Fig. 16. A configuration of the plasma-heated straight-grate process [8].

The next step of the iron ore induration project has been started by constructing a plasma-based pilot furnace. In October 2019, it was reported that RISE AB and LKAB had completed a 900-kW plasma torch Site Acceptance Test (STA), in which the thermal plasma would be installed to heat an induration furnace for the iron ore induration pilot test [25]. In this project, PyroGenesis Inc. was awarded the contract for supplying the plasma torch system. The installed plasma torch was based on their patented technology. PyroGenesis Inc., a plasma torch manufacturer from Canada, has previously proposed the concept of thermal plasma implementation for iron ore pelletization. A US patent application [26] has been granted in 2017, which contains several configurations of plasma torch installation to heat the induration of iron ore concentrate pellets in a tunnel furnace. Further report regarding the performance of the plasma-based furnace has not been found so far.

3.1.2 Iron-making

One of the examples of thermal plasma application for reduction processes is the hydrogen-plasma reduction process which has been investigated since the 1980s. The aim of these investigations is the development of hydrogen plasma smelting reduction as a CO_2 emission-free steel-making process. In this process, argon or nitrogen are commonly used as plasma gas and hydrogen as a reducing agent. Weigel et al. [27] studied the reduction of iron ores using an argon-hydrogen plasma in a lab-scale DC-plasma smelting furnace. The plasma torch was built with a thoriated tungsten electrode and a water-cooling system. An approximately 700 g of iron ore with a total Fe of 66.8% was used for each experiment. In the tests, the flow rates of the argon and hydrogen were set to nine and 10 L/min, respectively. It is reported that the degree of hydrogen conversion was between 43 – 50% with a total degree of iron reduction of approximately 75% in 35 min. Seftejani and Schenk [28] reported in their study regarding the kinetics iron oxide reduction rate using hydrogen, that its reduction rate in the plasma state is higher than that of the molecular state. So far, the development of the hydrogen-plasma reduction process is still limited at lab-scale tests, with no information further about related scale-up projects.

Another proposal of accommodating plasma in the reducing process is by adding the plasma torch in existing blast furnaces. In this way, the plasma torch is used to superheat the blast air at 1100 – 1600 °C; hence, the coke consumption rate and CO_2 emission can be reduced. A technical assessment of this process has been performed by HATCH based on the pilot-scale experiments conducted by AlterNRG [29]. It is reported in the assement that by superheating the blast air to 1600 °C through plasma heating, the CO_2 emission of blast furnaces can be reduced by 175kg CO_2/tHM [29]. However, the development of this technology is still in the pilot-scale with no further commercial-scale application has been reported.

Similarly, SKF (now ScanArc AB) founded the basic plasma process PLASMASMELT (as seen in **Fig. 17**) for pig iron production, which was further developed in the PLASMADUST modification - for non-ferrous metals dusts processing and PLASMACHROME - for FeCr production [30]. The shaft furnace is filled with coke, while in its stove zone are installed three plasma torches of 6 MW each. The powdered initial raw material is subjected to two-grade pre-reduction in two furnaces of fluidized bed type, using a reducing agent, the gas (carbon oxide), obtained in the shaft of the furnace. This gas acts both as transporting medium (to deliver the pre-reduced material and the low-quality powder coals into the plasma torch zone) and as a plasma gas [30].

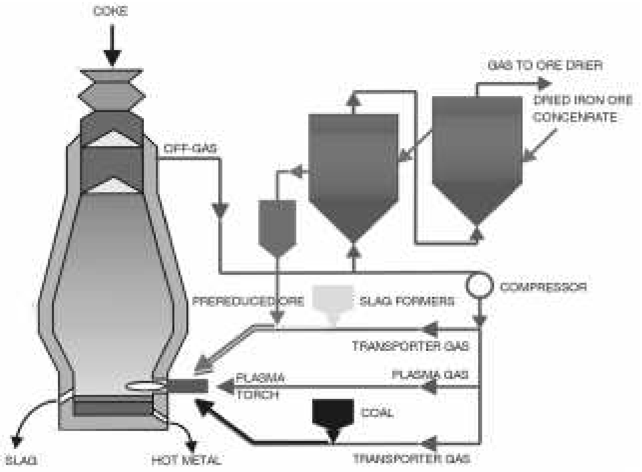


Fig. 17. Schematic diagram of PLASMAMELT developed by SKF (now ScanArc AB) in 1980s [30].

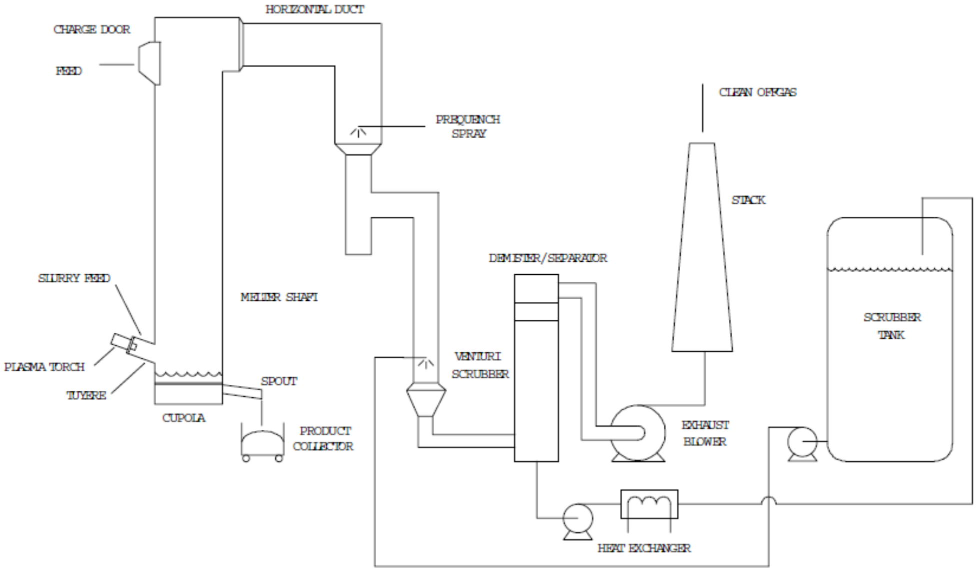


Fig. 18. Schematic diagram of a plasma-fired cupola system used for grey cast iron production at General Motors's foundry [31].

Adapting the similar concept as plasma-based blast furnace, Westinghouse started to develop a plasma fired cupola (PFC) since 1983 [31]. **Fig. 18** shows the schematic diagram of a PFC system. During 1989 – 2008, the General Motors' Powertrain plant located in Defiance, Ohio, used the PFC to produce grey iron for engine blocks and automotive castings. The foundry used six Westinghouse's MARC 11H plasma torches (power rating up to 2.4 MW) to increase the melt yield with a maximum furnace temperature of 1600 °C [31,32]. Operating experience suggested that plasma technology is economically suitable for iron melting as the PFC provided a strongly reducing atmosphere in the melting zone. No significant changes to foundry operations were required to employ the PFC system. The main advantage of using this cupola is reduced process gas velocities for the PFC compared to conventional cupolas due to lower coke usage [32].

In general, the plasma-based reduction technologies are still under development, and their industrial application is limited owing to the following challenges [30,32]:
- insufficient single power and operating reliability of existing non-transferred arc plasma torches,
- torch performance issue in the steelworks' dirt-laden/wet environment,
- inadequate electrode life,
- complicated exploitation scheme for maximum heat and reduction potential utilization of off-gases from plasma units,
- dynamic change of relation between electric energy and coke prices, and
- the metallurgical companies' lack of financing to develop into the commercial scale.

Recently, ScanArc AB has initiated an extensive project to develop the so-called IRONARC furnace. This project was initially announced in 2013, and the development is still ongoing until now. In this project, a novel pig iron production process is proposed in which plasma torches are used to replace conventional fossil fuel-based blast furnace fully. The IRONARC process exists in a pilot plant scale, and a schematic picture of the process can be seen in **Fig. 19**. In the process, electricity is used to generate plasma that melts the material by injecting gas, at high velocity, through a nozzle placed at the side of the reactor at a temperature around 4000 °C [33]. The gas is heated to around 20000 °C in the plasma generator (PG) but decreases to 4000 °C when injected into the slag. The slag temperature is around 1400 °C. There are two reduction steps: the first is where the slag that contains hematite (Fe_2O_3) is reduced to iron oxide (FeO), and in the second reduction step the FeO is reduced to Fe. For the first reactor step, the reducing agent is CO gas, which can be extracted from the second reactor [33]. Coals are only used in the final reduction step, where the iron oxide chemically is reduced to pig iron. Since all energy for heating the charged material comes from electricity, the opportunity to use renewable energy sources is given. The gas from the final reduction step is recirculated in the process, which gives an efficient energy usage of the gas [33].

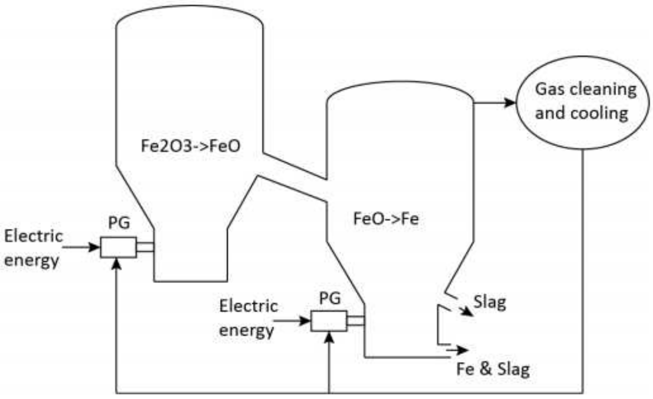


Fig. 19. Schematic diagram of IRONARC furnace developed by ScanArc AB [33].

3.1.3 Steel-making

3.1.3.1 Plasma arc melting furnaces

Plasma arc-melting furnaces are developed as an alternative to the classical electric arc melting. This technology has at least three different types which differ in regards to the power supply (DC or AC) and the plasma torch installation. **Fig. 20** shows the schematic diagram of these furnaces, which are Linde DC plasma furnace, Freital-Voest Alpine DC plasma furnace, and KRUPP AC plasma furnace [30]. These furnaces are commonly operated in the transferred mode under inert argon [34]. The Linde furnace type (operated in Russia) is a reconstructed classical electric arc furnace, where the graphite electrodes are substituted by plasma torches (cathodes) with an independent DC electrical power supply, and a water-cooled bottom electrode (anode). Meanwhile, in the Freital - Voest Alpine system, four DC plasma torches are located at the furnace jacket walls under a certain angle towards the metal bath. In the KRUPP AC melting plasma furnaces, the bottom electrode was avoided as it utilizes a starter DC plasma torch works as an electrode in the main powerful AC plasma torch. The possibility for the regulation of the plasma torches inclination towards the vertical furnace axis improves the furnace heating work and decreases the refractory lining consumption.

Compared to the classical electrical arc melting furnaces, the plasma-arc melting furnaces have the following advantages [30],
- increase the quality of the produced metal,
- improve the alloy elements assimilation grade,
- reduction of the specific electric energy consumption under increased output,
- enables the production of low carbon alloys, and
- reduction of the noise degree.

Nevertheless, the main problem of the high capacity power steel-making plasma-based furnaces is the short working life of the plasma torch electrodes (cathodes) under high current density. Hence, plasma melting technologies development is limited mainly by designing and manufacturing powerful metallurgical plasma torches with enough single power and reliability.

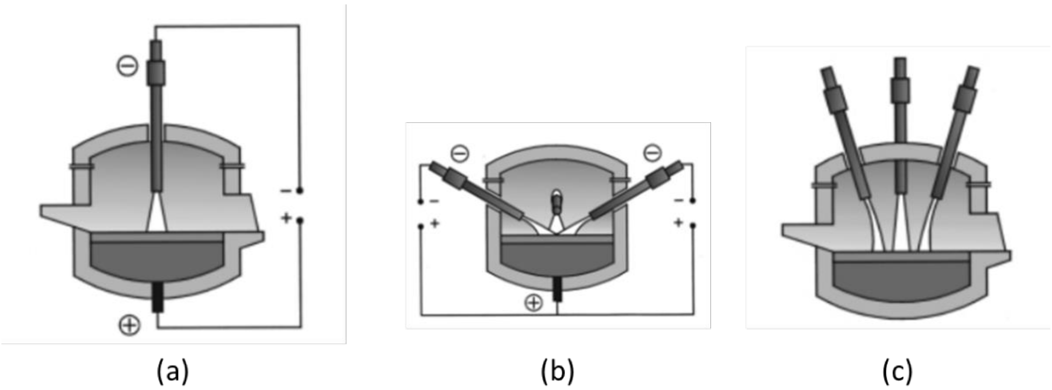


Fig. 20. Schematic diagram of various types of plasma-arc melting furnaces: (a) Linde DC plasma furnace, (b) Freital-Voest Alpine DC plasma furnace, and (c) KRUPP AC plasma furnace [30].

3.1.3.2 Ladle preheating

During the steel-making process, the ladle used to transfer molten steel have to be preheated, so that thermal shock and damage to the refractory lining and temperature drop in the ladle are minimized. Sufficient preheating is also necessary to avoid excessive heat losses of the liquid steel when it is filled into the ladle. Usually preheating of ladles has been performed with a gas-fired burner which injected a combustion flame into the interior of the ladle to the desired temperature.

Recently, KTH Royal Institute of Technology, ScanArc AB, Politecnico di Bari, and Sidenor Investigacion y Desarrollosa have initiated PlasmaPilot project. This project aims to test thermal energy input and demonstrate ladle preheating using plasma in an operational environment. The project consists of numerical studies of effective liquid steel temperature loss of subsequent heat, industrial measurement campaigns and laboratory testing of an improved refractory lifetime by minimized decarburization. The project work will be completed by an assessment of economic and environmental benefits and transferability directly into steel plant applications, which would lead to future steel plant implementation. No result has been reported so far from this project.

Previously, Krasnyanskii et al. [35] have reported an attempt to investigate the use of plasma torches for preheating of periclase-carbonaceous (PC) refractory, which is commonly used for steel ladle materials. The work consisted of an experiment and a Computational Fluid Dynamic (CFD) simulation. **Fig. 21** shows the schematic diagram of the experimental setup, in which PC-bricks are heated by a plasma torch. The anodic plasma torch was fixed, while the cathodic plasma torch was placed on a carriage that can be moved fore and aft by an electrically driven mechanism. The distance from the plasma-torch axis to the brick face was 150 mm. The current in the arc discharge during the experiment was 1000 A, the voltage was 150 V, and the consumption of plasma-supporting gas (argon) was 17 nm^3/h [35]. The result of the study suggests that it is challenging to accurately model the processes of drying and heating because of the changing thermal characteristics of PC-refractories. Moreover, the smooth surface of an unburnt brick reduces the effectiveness of heating [35].

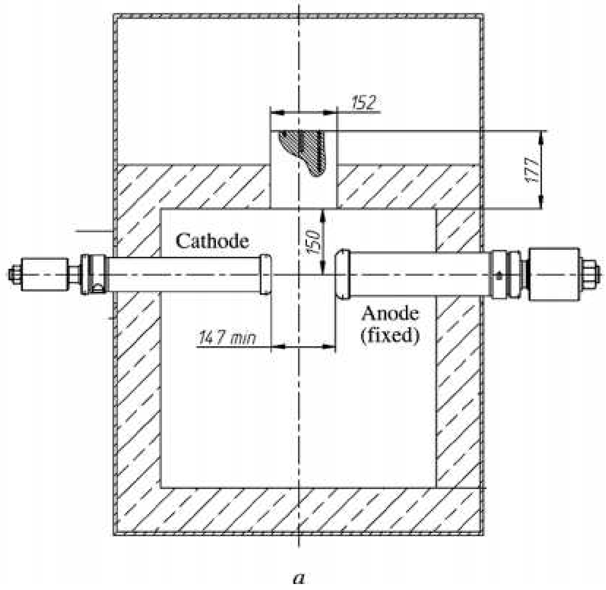


Fig. 21. Schematic diagram of the experimental setup for plasma-based ladle preheating [35].

3.1.4 Steel heat treatment

Most of the available report or studies to mitigate the CO_2 emission of the steel heat treatment furnace are mainly focused on the use of oxy-fuel combustion. This technology can be considered mature. Since 1990, Linde Gas has applied oxy-fuel combustions for rolling mills, forge shops and annealing lines [36]. By using oxy-fuel combustions, fuel consumption can be reduced by up to 50% and reduces CO_2 levels correspondingly. Further, NO_x levels can also be kept low, as there is no nitrogen in the oxyfuel combustion process. Furnace throughput can be boosted by up to 50%, providing extra production capacity [36].

The effect of the oxy-fuel combustion on the steel oxidation at high temperatures during forging, reheating, and heat treatment furnaces have also been reported [37,38]. A work based on a computational fluid dynamics (CFD) investigation by Schluckner et al. [39] reports the prediction of scale formation of steels in the air- and oxygen combustion atmospheres. In this study, a natural gas-fired furnace operates at 750 – 1200 °C is simulated to predict local and temporal scale growth rates of steels. The study demonstrates that even small variations of the local species concentrations at the steel surfaces can cause a noticeable impact on the scale formation rate. An increment in the amount of steam in the flue gas accelerates scale formation rates. In addition, the study suggests that the amount of excess oxygen needs to be closely controlled and monitored when the steel reaches temperatures above 750 °C to avoid excessive scale build-up.

The possibility of the electrification of steel heating furnaces has been discussed in the report *FlexVärmeStål* published by Jernkontorets [40]. The report proposes several configuration systems to heat high-temperature furnaces employing electrical induction heaters. These systems include the combination of electrical and regenerative heating sources, recuperative combustion system coupled with induction heating, and regenerative combustion system coupled with the induction system. However, neither detail simulations nor experimental tests of such configurations have been reported so far.

To the best of authors' knowledge, so far, there is no information available regarding the application of plasma torches for heating furnaces in the steel industry.

3.2 Other metallurgical applications

3.2.1 Plasma spraying

Fig. 22 (upper) shows the schematic diagram of the thermal plasma spray coating process. Which is commonly use non-transferred arc DC plasma torches with a hot cathode and a water-cooled ring anode. The cathode material usually is thoriated tungsten. The process can be carried out in open air or under controlled conditions in a chamber where ambient conditions can be controlled. Plasma gases used include argon and nitrogen often mixed with hydrogen or helium to enhance its thermal conductivity and, hence, to increase in-flight heat transfer to the injected powders [13]. The torch power is typically below 100 kW, though some plasma spray torches have been reported to operate at power levels up to 200 kW [13]. One of the examples of commercial torches for plasma spraying is Oerlikon-Metco's PTF4 torch showed in **Fig. 22** (lower).

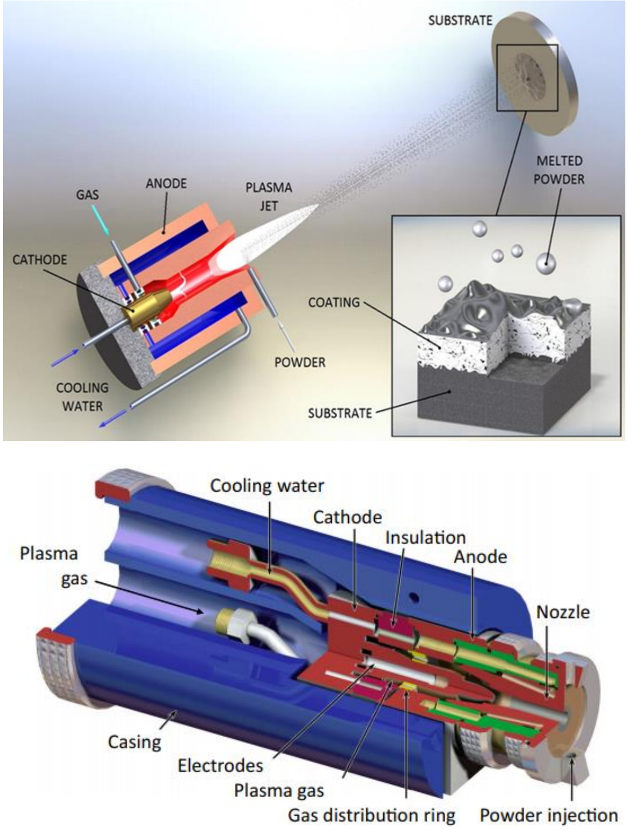


Fig. 22. Upper: schematically the principal features of the thermal plasma spray coating process. Lower: PTF4 thermal spray torch by Oerlikon-Metco [13].

Table 3. Specification of various application of thermal plasma for metallurgical applications [41].

Plasma torch manufacturers	Plasma power (kW)	Electrode	Applications
Metco	100	Tungsten-copper	Plasma spraying
Ionarc	350	Tungsten-copper	Zirconia production
Linde-Retech	700	Copper	Plasma melting
Daido	1000	Tungsten-copper	Scrap remelting
Westinghouse	2000	Copper	Scrap melting
PEC	4500	Copper	Ladle heating
Tioxide	5000	Copper	Titanium dioxide
Aero-Spatiale	5000	Copper	Ferro-manganese
SKF/ScanArc	7000	Copper	Recovery from dust
Voest-Alpine	7500	Tunsten-copper	Steel remelting
Huls	8500	Steel/copper	Chemical synthesis

3.2.2 Metal recovery and recycling

The utilization of plasma technologies for metal recovery and recycling can be considered as the most mature application of plasma technologies. This is especially shown by various commercial-scale plants that have been successfully built and operated around the globe. Some examples of plasma applications in this field can be seen in **Table 3**.

In the past two decades, ScanArc AB has been involved in the development of various commercial-scale metal recovery and recycling plants utilizing their DC plasma torches. The processes are developed based on their ARCFUME furnace, which its schematic figure is shown in **Fig. 23**. Among these plants are owned by the following companies [42],

- Metallo Chimique for the recovery of copper and zinc from a copper/zinc converter slag,
- EnvironPlasma for the recovery of valuables and energy from electronic scrap,
- BEFESA ScanDust for the recycling of stainless steel filter dust for recovery of valuable metals,
- ValEas AB for the recovery of valuable metals from rechargeable batteries, and
- Nyrstar Høyanger for the recovery of copper, zinc, lead, indium, and germanium from leach residue.

Nevertheless, many of those companies have closed their operation due to various reasons, including the failure to secure reliable supplies of feedstock [43].

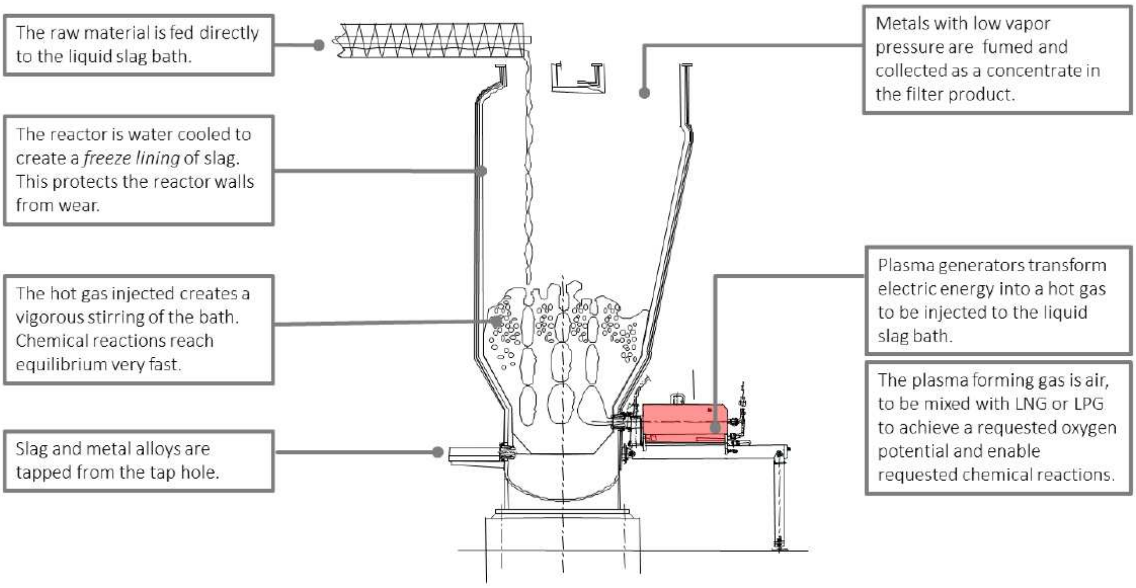


Fig. 23. Schematic figure of ARCFUME developed by ScanArc with key features [44].

3.3 Solid waste treatment

The use of thermochemical techniques for waste disposal and waste-to-value processing has been adopted widely to treat Municipal Solid Waste (MSW), industrial waste, and hazardous waste. This technique includes incineration, gasification, and pyrolysis. Among these thermal conversion methods, high-temperature gasification processes (e.g. plasma gasification) are regarded as viable candidates for combined energy and material valorizations in the form of syngas and vitrified ash residue [45]. Plasma gasification has mainly been used for treating hazardous waste, and its use for waste-to-value processing is relatively new [46]. It is considered that the plasma stimulates higher syngas yields than conventional gasifiers. As it works at very high temperatures, often higher than 5000 °C, the inorganic waste components can be removed as inert vitrified slag with minimal toxic element leachability [47]. Moreover, the amount of toxic materials in the product syngas is much lower than incineration and conventional gasification techniques [47]. **Fig. 24** shows typical plasma gasification systems developed for waste-to-value schemes.

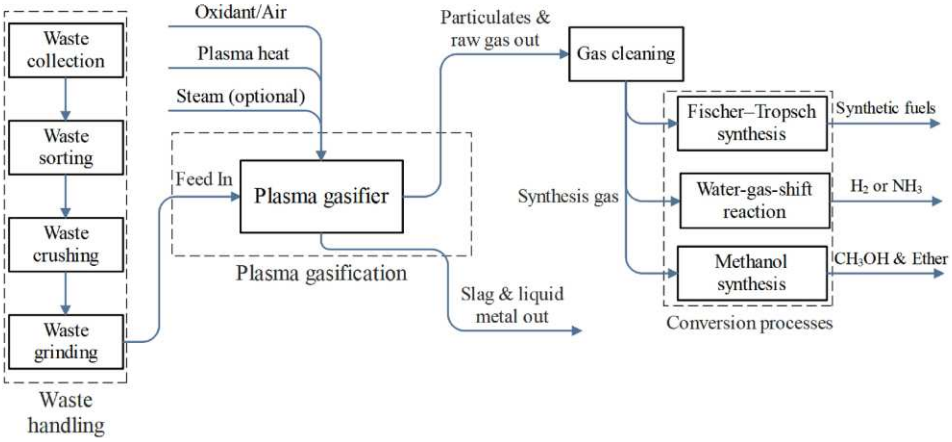


Fig. 24. Schematic diagram of typical plasma gasification systems [46].

According to Sanlisoy et al. [48], the type of the plasma gasification reactors can be classified into plasma fixed bed reactor, plasma moving bed reactor, plasma entrained bed reactor or plasma spout bed reactor. In plasma fixed bed reactor, the gasification material is stationary in the reactor, and the plasma is injected through it where the syngas is extracted from the upper portion and the vitrified ash (slag) from the bottom of the reactor. In the case of plasma moving bed reactor, there is a continuous material feeding on up to down and plasma is injected to the inflow of the material. In plasma entrained bed reactor, the material is injected through the plasma medium. Plasma spout bed is a combination of the fluidized bed and plasma spouting.

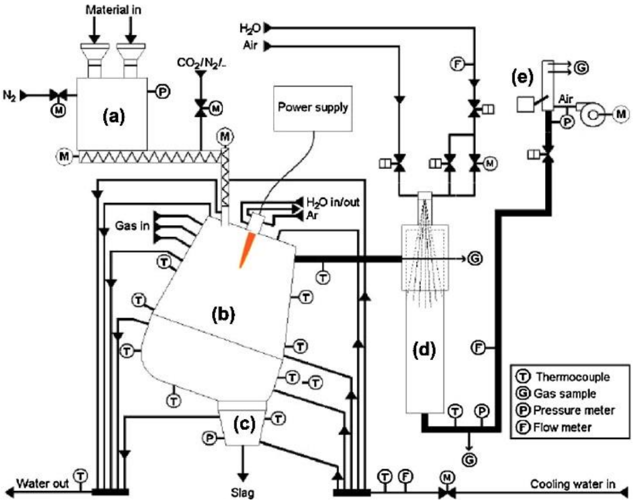


Fig. 25. Schematic of the reactor system developed by the Institute of Plasma Physics ASCR. The plasma jet is marked in orange and (a) the material hopper; (b) the reactor vessel; (c) the slag collection bucket; (d) the quenching chamber and (e) the afterburner ([49]).

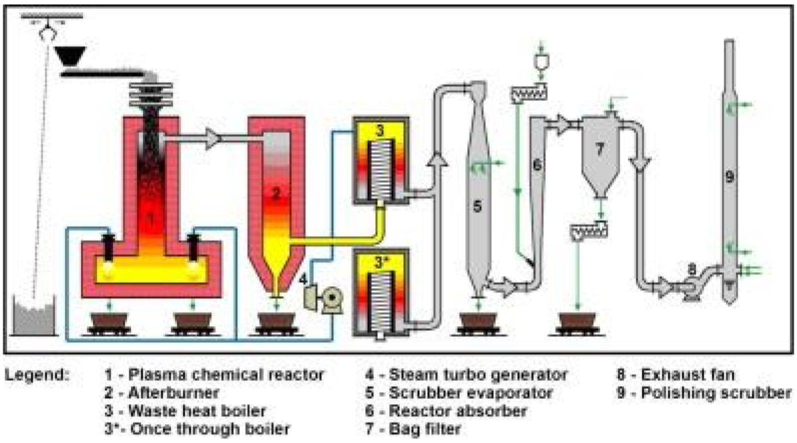


Fig. 26. Illustration of the Plasma Gasification Melting plant developed by [50].

Table 5 lists the plasma gasifier manufacturers around the globe. Even though there is a tremendous number of gasifier manufacturers, the number of commercial applications of plasma gasification is still limited. This mainly due to various challenges associated with plasma gasification such as its being a relatively new technology, requiring high capital & operational costs, is a highly energy-intensive process, has only a moderate technology & community readiness level, the requirement of proper waste sorting, the limited technology commercialisation success, and currently limited process understanding [46].

As of 2020, Mukherjee et al. [47] reported that no commercial MSW plasma gasification technology is known to be operational in the US. Most of the plasma gasification systems are currently still in the demonstration or experimental validation stage for industrial and pilot-scale use. For example, PyroGenesis Canada Inc. installed and operated the first commercial plasma gasification system at the US Air Force base for processing MSW, hazardous, and biomedical waste and generated electricity from the syngas. However, currently, this facility is not in regular operation. A few projects in the developmental stage include InEnTec Chemical LLC, Geoplasma Inc., Green Power Systems LLC, and GasPlasma technologies [47].

Table 4. Specification of the various lab- and demonstration-scale of developed plasma gasifiers for waste treatment.

Companies/Institutions	Capacity (kg/h)	Plasma power (kW)	Plasma gases	Feedstocks	Cold gas efficiency (%)	References
Institute of Plasma Physics ASCR	29	90 – 160	Steam, O_2, CO_2	Biomass, MSW	42 – 53	[49,51]
Environmental Energy Resources Ltd.	300	240 – 260	Air	MSW	30 – 60	[50]
Postech	400	200	Air	MSW	n.d.	[52]
AlterNRG	30000	3200	Air	MSW, auto shredder residue	79	[53]

Table 5. List of manufacturers of plasma gasification reactor for solid waste treatment [54].

Manufacturers	Nation	Feedstocks
AlterNRG	Canada	MSW, RDF (refuse-derived fuel), ASR, tire, coal and wood, hazardous waste, petcoke
Advanced Plasma Power (APP)	UK	RDF
Bellwether Gasification Technologies	Germany	MSW, RDF
Bio Arc	USA	Agricultural waste, medical waste
Blue Vista Technologies	Canada	MSW, hazardous liquids and gaseous wastes
Environmental Energy Resources (EER)	Israel	MSW
Encore Environmental Solutions	USA	Hazardous waste
Enersol Technologies	USA	LLR (low level radioactive), munitions
Enviroarc Technologies	Norway	Tannery waste, other hazardous waste, ash
Europlasma	France	Hazardous waste, ash, MSW, tires, syngas cleaning
GS Platech	Korea	MSW, biomass, ASR, industrial waste, hazardous waste, sludge, radioactive waste
Hera Plasco	Spain	MSW
Hitachi Metals	Japan	MSW and ASR, MSW and sewage sludge
Hitachi Zosen	Japan	Ash
Hungaroplazma Services	Hungary	MSW
InEnTec	USA	Medical waste, hazardous waste
International Scientific Center of Thermophysics and Energetics	Russia	Transformer oil, pesticide, medical wastes, waste oil and coal slimes
Kawasaki Heavy Industries	Japan	PCBs and asbestos
Kinectrics	Canada	MSW, waste plastics
Mitsubishi Heavy Industries	Japan	Ash
MPM Technologies	USA	ASR, sewage sludge, waste tires and petcoke, biomass
MSE Technology Applications	USA	Military, hazardous waste
Plasma Energy Applied Technology (PEAT) International	USA	Hazardous waste, medical, industrial process and pharmacy waste
Phoenix Solutions	USA	Ash
Plasco Energy	Canada	MSW
Pyrogenesis	Canada	Shipboard waste, industrial waste
Radon	Russia	LLR and hazardous waste
Retech Systems	USA	Hazardous wastes, LLR wastes
SRL Plasma	Australia	Solvent, waste chemicals and CFC’s (chlorofluorocarbon)
Startech Environmental	USA	MSW

Tetronics	UK	Ash, APC residues and hazardous waste, catalyst waste, steel plant wastes, hazardous waste, RDF

3.4 Cement production

Vattenfall and Cementa AB have initiated CemZero; a project focused on the reduction of emission by replacing fossil fuel with electric-based heating sources. As a part of the project, a feasibility study has been done to evaluate the potential of using thermal plasma technologies as the primary heat source [55]. The thermal plasma technology was proposed to be used for the calciner and rotary kiln under CO_2 and air atmosphere, respectively. In this study, tests with a plasma generator of 300 kW were conducted in collaboration with ScanArc to evaluate the possibility of regular quality cement clinker with plasma gas as heating source as can be seen in **Fig. 27**. The study proposed a process flow diagram with the application of thermal plasma heating system, as shown in **Fig. 28**. The result of the study indicated that the concept of using plasma generators in a pre-heater/pre-calciner kiln system could be considered as the leading technology path for future development. However, there are challenges of the technology related to the possible use of carbon dioxide as carrier gas as well as requirements on gas-tight systems. Therefore, the study suggested a further investigation in a larger pilot-scale plant to address these challenges.

Fig. 27. Test configuration of plasma generator from ScanArc AB together with rotary batch kiln from Cementa Research [55].

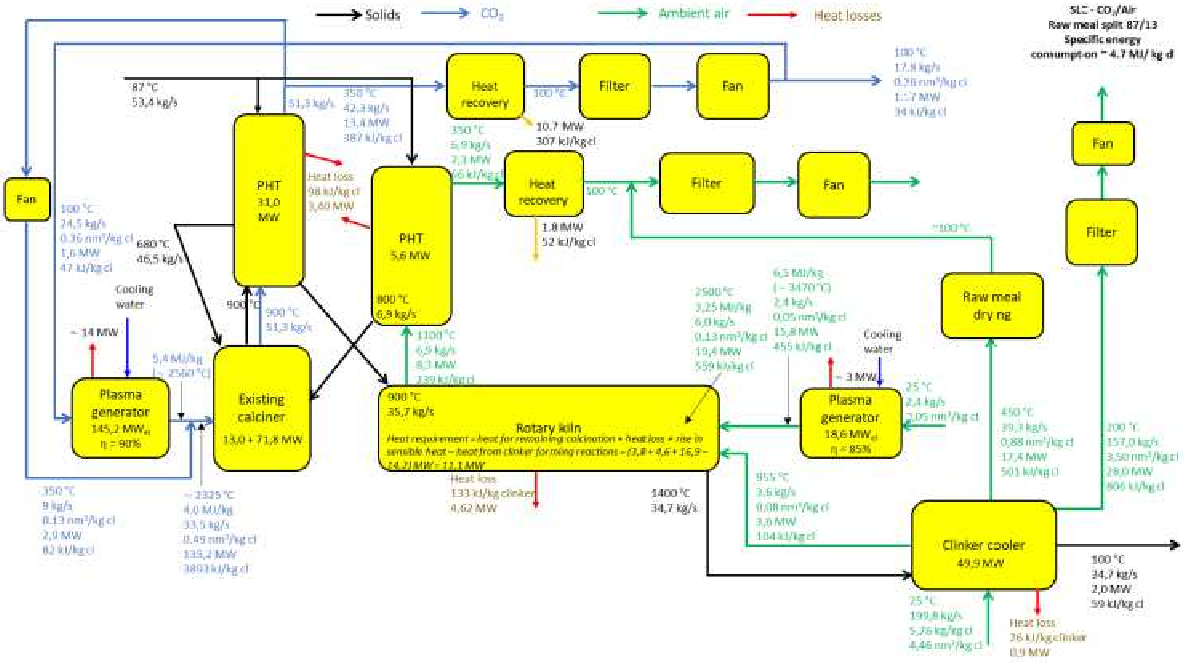


Fig. 28. Process flow diagram and selected results for the plasma-based cement production system. The plasma gas is CO_2 for the calciner and air for the rotary kiln [55].

Further, the outcome from this economic analysis indicates that the production costs for an electrified cement process are approximate twice the costs of a reference cement plant operating as of 2018 in Sweden. The reference cement plant refers to a fossil-based combustion process with no carbon capture technology installed. **Table 6** shows the details of the capital and production costs for different plant scenarios. However, the study also shows that electrification as a carbon capture technology compares economically well to other carbon capture technologies of today. A detailed comparison indicates a higher production cost for a post-combustion amine method. In addition, the electrification scenario has significantly lower total energy consumption than the post-combustion amine method. All this, together with the forecasted prices for raw material, energy and carbon dioxide emissions, means that a fossil-free electricity-based cement process appears to be economically viable. A full scale new electric-based cement production plant is expected to be commissioned by 2030 [56].

As a continuation of the work, a new project (funded by Energimyndigheten) has been initiated in 2019 by the collaboration of Cementa AB, Heidelberg Cement AG, STENA Aluminum, and STENA metal. Pilot-scale experiments will be carried out in close collaboration between the industrial partners, Chalmers, and Umeå University. The studies on this project will be focused on the investigation of radiant heat transfer and to some extent, also convective heat transfer. No result has been reported so far from this project.

Table 6. Capital and production costs of cement for different plant scenarios* [55].

Cost	Reference plant (fossil-fuel burner)	Reference plant with CCS (amine-based)	Electrified plant (plasma torch)
Capital cost (Million €)			
Total equipment cost	145.0	145.0	143.9
Design & engineering	10.0	10.0	10.0
Construction	45.0	45.0	40.5
Other costs	5.0	5.0	5.0
EPC services	5.0	5.0	5.0
CO_2 processing unit (CPU)	-	28.5	19.2
Other related costs for carbon capture	-	16.7	5.0
Electrical boiler	-	32.3	-
Post combustion	-	52.5	-
Plasma torch system	-	-	47.5
Total installed cost	**210.0**	**340.0**	**276.2**
Owner cost (5%)	10.5	17.0	13.8
Contingencies (5%)	10.5	17.0	13.8
Total capital required	**231.0**	**374.0**	**303.8**
Production cost (€/ton cement)			
Fuel	4.2	4.2	-
Power	3.9	29.4	41.7
Capital	24.3	39.4	32
Other variable O&M	5.3	8.9	7.3
Fixed O&M	14.9	19.6	19.1
Total production cost	**52.6**	**101.5**	**100.0**

**The plant is assumed to have a capacity of 1.35 Mton cement per year, and be located in Sweden. The calculation are expressed in Euro € applicable to 2018.*

Table 7. Summary of recent plasma torch projects by Swedish companies/institutions.

No.	Project name & year	Institution & funding	Year	Application & aims	Plasma torch specifications	Results
1	**PlasmaPilot –** Flexible Ladle Preheating Procedures using Plasma Heated Refractory*	- KTH - ScanArc AB - Politecnico di Bari - Sidenor Investigacion y Desarrollosa. Funding by the EU Research Fund for Coal and Steel	2020 – ongoing	*Application: Ladle in steel-making* This project aims to test thermal energy input and demonstrate ladle preheating using plasma in an operational environment. The project consists of numerical studies of effective liquid steel temperature loss of subsequent heat, industrial measurement campaigns and laboratory testing of an improved refractory lifetime by minimized decarburization. The project work will be completed by an assessment of economic and environmental benefits and transferability directly into steel plant applications, which would lead to future steel plant implementation.	N/A	No result has been reported so far.
2	Plasma burner for zero greenhouse gas emissions in the process industry*	- Luleå tekniska Universitet - RISE ETC Funding by Energimyndigheten	2020 – ongoing	*Application: Heating furnaces in process industries* The general aim of this research project is to contribute with basic knowledge about plasma technology through fundamental research. It aims to contribute to the electrification of the process industry in the long term by replacing fossil fuels in the process industry's combustion processes with plasma torches.	A lab-scale plasma torch is available at RISE ETC which specification as follow: - 18 kW - DC plasma torch - Plasma gas: N_2, air, CO_2, argon - Manufactured by Plasnix (South Korea)	No result has been reported so far.

				The goal of the project is to increase the knowledge of plasma torches concerning: - How do different carrier gases affect the generation of the plasma flame? - How can the plasma flame be generated as efficient as possible? - How to control the temperature and chemical composition of the flame in the best environmental friendly way? The project consists of two work package which is CFD modelling of plasma at LTU, and investigation by a lab-scale plasma torch at RISE ETC.		
3	**CemZero** – Heat transfer with plasma in rotary kilns*	- Cementa AB - Heidelberg Cement AG - STENA Aluminum - STENA Metall Funding by Energimyndigheten	2019 – ongoing	*Application: Cement kiln furnace and aluminium recycling furnace* The proposed project aims to generate the knowledge required to move from today's fossil/waste-fuel based processes to electrified systems by the use of state-of-the-art plasma-torches. Specifically, the project aims to enable the use of plasma torches in rotary kilns to effectively reduce carbon dioxide emissions without risking the quality of the product or influence productivity. Pilot-scale experiments will be carried out in close collaboration between the industrial partners, Chalmers, and Umeå University. The studies on this project will also be focused on the	N/A	No result has been reported so far from this project. However, Cementa AB has reported a preliminary assessment of plasma utilization in cement kilns (in 2018) before this project. The report stated that the electrification of cement kiln by means of plasma torch has a better potential for capturing CO_2 emission than the post-combustion carbon-capture method. This is indicated by the significantly lower total energy consumption than the post-combustion amine method [55].

				investigation of radiant heat transfer and to some extent, also convective heat transfer. To enable the overall goals of the CemZero program, this project aims to characterize a full-scale process so that it is possible to evaluate the implementation of a full-scale plasma torch concerning the following aspects, • a better understanding of the relationship heat transfer and temperature profile that can further be related to the chemical course, • sharply reduced emissions from northern European aluminium smelting, • reduced energy use in the return melting of aluminium, • better process control about radiant heat transfer, which also links to fuel consumption, product quality and capacity.		
4	Iron ore pellet induration furnace [8,24,25]	- LKAB - RISE ETC - Chalmers	2018 – ongoing	*Application: Induration furnace* The project aims to replace the conventional fossil fuel burner in the iron ore induration furnace by plasma torches. This project is a part of HYBRIT initiatives which develops a process for fossil-free steelmaking by 2035. The project has been started by completing a simulation work through the collaboration with Chalmers. The next step of the iron ore induration	A DC 900-kW plasma torch manufactured by PyroGenesis Inc is used for the pilot-scale tests at LKAB.A	From the simulation assessment work, the following results are obtained, - retrofitting plasma torches in place of fossil fuel burners in a pelletizing plant with a 40 MW thermal input has the potential to reduce CO_2 emissions by up to 140 000 ton per year, - as the process air is heated by electricity instead of combustion, it contains less

				project has been started by constructing a plasma-based pilot-scale furnace together with RISE ETC at Lulea.		water vapour; hence, it can provide a higher drying efficiency, - significant amounts of NO_x is produced when hot plasma gas mixes with the air. The formation of NO_x is dominated by the thermal NO_x mechanism, and the reaction rate increases exponentially with temperature, - reburning is the most promising out of the studied reduction strategies, with NO_x reduction of up to 65 % in the simulations. No result is available from the 900-kW plasma torch tests so far.
5	Recycling platinum group metals from autocatalysts	- ScanArc AB Funding by Energimyndigheten	2018 – 2020	*Application: Metal recycling* The project aims at demonstrating the first economically and technically feasible method for recycling platinum group metals from silicon carbide car catalysts. Catalysts are used in vehicles for cleaning exhaust gases and contain platinum group metals embedded in a catalyst mass. When the EU in 2002 tightened the requirements for emissions from cars, a new type of catalytic converter based on silicon carbide (SiC) was introduced. Handling these with the traditional recycling method causes losses of over 50% of the metals. With this innovation called SiCAT, the	N/A	N/A

				recycling rate increases to more than 99%. The Project aims to optimize the method and demonstrate the technology with the overall purpose of establishing it as a market leader. The method has a great potential to reduce the shortage of these critical metals and increase the competitiveness of Swedish and European industry.		
6	**IronArc** – A Novel Method of Energy Efficient Iron Production [57,58]	- KTH - ScanArc AB Funding by Energimyndigheten	Completed in 2019	*Application: Iron-making (reduction furnace)* The project aim was to evaluate the technical possibilities to construct a full-scale plasma-based iron production process that has the potential to replace existing blast furnaces with an energy savings potential of 977 kWh/ton pig iron. The target production volume for this project was set to 500 000 ton pig iron per year, with annular savings of 489 GWh, a decrease of 382000 tons of CO_2 and 160000 tons of coke. To achieve these aims, both theoretical, numerical and experimental investigations were performed in this project.	A demonstration-scale experiment is carried out by using a plasma torch with specification as follows: - 3 MW - DC plasma torch - Plasma gas: Air - Current: 150 – 300 A - Manufactured by ScanArc AB	Based on the outcome of the project and industrial experiments and other processes, there is no obvious technical limitation to achieve a large-scale plasma-based iron-making process that in the future, can replace existing blast furnaces.
7	**CarboneXt PACE** (Plasma Assisted Carbon Extraction)*	- CarboNext AB Funding by Energimyndigheten	2017	*Application: Fuel productions* CarboneXt PACE (Plasma Assisted Carbon Extraction) is a technique for refining biogas and other hydrocarbons to solid carbon structures and hydrogen. The process enables control over the kinds of	N/A	N/A

carbon structures produced, thus providing new market opportunities for the European biogas industry, which is currently struggling with profitability problems. The purpose of the project is to protect IP-rights to the solution and conduct a technical and financial prestudy as a basis for a first commercial facility

**the descriptions of these projects are obtained by directly contacting the funding agency or the institutions/companies.*

4 Conclusions

From the literature review, conclusions can be drawn as follows,

- DC plasma torches are currently the most widely used plasma type for industrial processes. It is favourable than other types of thermal plasma owing to the less flicker generation and noise, better control, more stable operation, lower consumption of electrode, lower power consumption, lower refractory wear.

- Current applications of thermal plasma torches are mainly in the area of melting furnaces for the industrial metallurgical process. The application of these torches are considered mature as a wide range of materials can be treated.

- Within the scope of iron- and steel-making processes, several novel applications of thermal plasma have been proposed with the aims of reducing CO_2 emissions. These applications include the induration of iron ore pellets, replacing conventional fossil-fuel based blast furnace, arc melting furnaces, and ladle preheating. However, those applications are mainly still in the stage of early development or pilot demonstration. Further, no information is currently available regarding the utilization of thermal plasma for steel heating furnaces.

- Outside the field of metallurgy, thermal plasmas have been widely adapted for waste-to-energy schemes by plasma gasification. Even though some of the plasma manufacturers have successfully developed large-scale gasifier, a very limited number of commercial MSW plasma gasification technology is known to be operational around the globe. There are also projects currently work with the installation of plasma torches for cement kiln. However, the works are still limited in the simulation works, and the results from the pilot- or commercial-scale operations are still unknown.

- Typical gases used for plasma torches in metallurgical furnaces include mainly inert gases such as argon and nitrogen. In contrast, the use of air and steam for plasma gas is widespread in the field of the gasification process.

- The operating parameters of the plasma torch should be carefully considered when it comes to their use for steel heating furnaces. This is especially true in the case of the selection of the plasma gas agents. For example, it is known that changing the conventional burner with air plasma torch could potentially increase NO_x emission due to the higher temperature that leads to the thermal NO_x formation. The use of H_2 or steam as plasma gas may prevent the formation of thermal NO_x. However, at high temperatures (> 1000 °C), the present of steam significantly increase the oxidation rate of certain refractories and steel materials, which may negatively affect the operation of the furnace, as well as the quality of steel products.

- Overall, some common challenges often hinder the successful operation of thermal plasma technologies at the industrial level. These challenges include it is a relatively new technology, requiring high capital & operational costs, is a highly energy-intensive process, has only a moderate technology & community readiness level, the limited technology commercialization success, etc.

To summarize, in general, current information regarding plasma-technology utilization for electrification of conventional industrial furnaces are still lacking. Most of the current thermal plasma applications are focused for the metallurgical processes, in which plasma torches are used to replace other electrical-based sources of heat. Whereas, information on the use of thermal plasma for the alternative of fossil-fuel burners in other process industries is still scarce. Even though thermal plasma torches have shown promising potentials, extensive developments at conceptual, simulation, lab-scale, and pilot-scale levels are still needed to actualize their use for specific industrial heating furnaces, such as steel heating furnaces.

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