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Vasyl Stefanyk Precarpathian
National University

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Kali Charan Sabat

# Physics and Chemistry of Solid State Direct Reduction of Iron Ore by Hydrogen Plasma

*Maulana Azad National Institute of Technology, Bhopal, Madhya Pradesh, India, kcsabat@gmail.com*

Generally, iron is produced from iron ores by using carbon from coal. The production process is consisting of many stages. The involvement of multi-stages needs high capital investments, large-scale equipment, and produces large amounts of carbon dioxide ($CO_2$) responsible for environmental pollution. There have been significant efforts to replace carbon with hydrogen ($H_2$). Although $H_2$ is the strongest reductant, it still has thermodynamic and kinetic limitations. However, these thermodynamic and kinetic limitations could be removed by hydrogen plasma (HP). HP comprises rovibrationally excited molecular, atomic, and ionic states of hydrogen. All of them contribute to thermodynamic advantage by making the Gibbs standard free energy more negative, which makes the reduction of iron oxides feasible at low temperatures. Apart from the thermodynamic advantage, these excited species increase the internal energy of HP, which reduces the activation energy, thereby making the reduction easier and faster. Apart from the thermodynamic and kinetic advantage of HP, the byproduct of the reaction is environmentally benign water. This review discusses the physics and chemistry of iron ore reduction using HP, emphasizing the solid-state reduction of iron ore. HP reduction of iron ore has been found to be a high-potential and attractive reduction process.

**Keywords:** reduction of iron ore, direct reduced iron, sponge iron, iron production process, hydrogen plasma, non-thermal plasma, plasma physics, plasma chemistry, plasma thermodynamics, plasma kinetics.

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## Introduction

Currently, iron is produced from medium or high-grade iron ore by using carbon; a process called carbothermic reduction. The carbon comes from coke, which is obtained from the carbonization of coking coal. Both medium/high-grade iron ore and coking coal are depleting at a very fast rate across the world. Therefore, the future supplies of these raw materials will be limited. The present carbothermic reduction process consists of many unit steps/processes like coke-making, pelletization, sintering, etc. These unit steps/processes are causing many environmental problems, huge costs, and facing strict environmental regulations due to the emission of greenhouse gas carbon dioxide ($CO_2$). A huge amount of $CO_2$ (1.8 tonnes) is produced per tonne of steel [1]. The current steel production is 1869 million tonnes [2], which is going on increasing year by year. This huge emission of $CO_2$ raises the question of the survival of living beings by causing severe environmental natural disasters. If this rate of $CO_2$ emission continues, there will be shortage of breathing air and questions of survival. Due to this fact, environmental regulations are becoming stricter day by day. In fact, there have been significant pressures on the steel industries across the globe to reduce $CO_2$ emissions. However, the current ironmaking technology processes, i.e., reduction of iron ores in solid-state (called direct reduced iron or sponge iron) and reduction in the liquid state (called pig-iron), have attained maturity. The operations in these matured technologies have almost attained the thermodynamic equilibrium, thereby eliminating the possibilities of decreasing the $CO_2$ emissions [3]. Therefore, a massive amount of money (~ US $1 billion) has already been invested in R&D projects [1,4] in search of low-carbon breakthrough technologies.

# I. Low-carbon Footprint Technology - Hydrogen gas

In search for some low-carbon footprint technologies, hydrogen ($H_2$) has been found as the most suitable candidate to replace carbon [1, 4-5]. $H_2$ is the strongest candidate because it possesses thermodynamic and kinetic advantages [1, 4, 14-19, 6-13] compared to $CO_2$. Also, the reduction product is environmental friendly water ($H_2O$) and a very low quantity of $H_2$ consumed per tonne of iron. It is shown in Table 1.

As shown in Table 1, the production of 112 tonnes of Fe requires 36 tonnes of carbon for reduction, producing 84 tonnes of carbon monoxide (CO). Similarly, production of 112 tonnes of Fe requires 18 tonnes of carbon for reduction, producing 66 tonnes of $CO_2$. The amount of CO and $CO_2$ produced in these reactions is huge. The huge amount of carbon required for these reduction reactions is generally obtained from coke, produced from coking coal. The coke making from coking coal is not environmental friendly, and the availability of coking coal is scarce. Also, the huge amount of CO and $CO_2$ produced by these reactions are responsible for polluting the environment and causing a greenhouse effect. On the other hand, when $H_2$ is used as a reductant in place of carbon, 112 tonnes of Fe require only 6 tonnes of $H_2$. It produces 54 tonnes of $H_2O$, which is environmentally benign; therefore, no environmental issue.

Concerning availability, the availability of coking coal is scarce, but the availability of $H_2$ is plenty. Also, $H_2$ is extracted from $H_2O$ by $H_2O$ splitting, and there is a huge amount of $H_2O$ available in nature. Apart from the electrolysis of $H_2O$, $H_2$ is also produced by other processes, e.g., reforming methane. Solar energy is also being utilized to produce $H_2$ by using solar cells to provide the necessary electrons for electrolyzing $H_2O$, or by using sunlight directly on semiconductors immersed in $H_2O$ to cause photocatalytic $H_2O$ splitting [20,21]. $H_2$ production from other sources have been reported in an earlier publication [1].

In addition to lower consumption and the ease of availability, $H_2$ also possesses many technical advantages: (a) CO and $CO_2$ are avoided because the product gases are mixtures of $H_2O$ and $H_2$, (b) the reduction rate becomes faster because of the small size of $H_2$, (c) avoids the carbon content in the produced Iron, (d) elimination of costly and polluting cokemaking step, (e) the consumption of energy decreases by 57 %, (f) the emission of $CO_2$ decreases by 96 pct. These advantages mainly come from eliminating the problematic unit steps/processes like cokemaking and sintering or pelletization [22]. Despite these enormous advantages, $H_2$ could not be a large-scale industrially accepted technology to date, due to the limitations imposed by thermodynamic and kinetics.

# II. Hydrogen Plasma - Novel Production Process

The thermodynamic and kinetic limitations of $H_2$ could be successfully removed by HP [1, 4, 6-10, 23-25] due to the excited species present in it. These excited species are rotationally-excited and vibrationally-excited hydrogen molecules ($H_2^*$), atomic hydrogen (H), and ionic hydrogen ($H^+$), etc. Apart from removing the thermodynamic and kinetic limitations of $H_2$, HP can also be produced easily by several methods. They can be produced by the application of direct current (DC), alternating current (AC), radiofrequency (RF), microwave (MW), or any other electromagnetic (EM) field. Recently, by using a simple microwave setup, several metals and alloys could be produced by HP, for example, iron from hematite ($Fe_2O_3$) and iron ore [1, 6, 23], Copper from Cupric oxide (CuO) [8], Cobalt from Cobalt oxide ($Co_3O_4$) [7], and alloys like FeCo alloy from $Fe_2O_3$ and $Co_3O_4$ mixture [9], CuNi alloy from CuO and NiO mixture [10], CuCo alloy from CuO and $Co_3O_4$ mixture [25], etc. The production of other metals by these HP methods has been extensively reviewed by Sabat et al. [1,4]. Iron, being the largest produced metal, has a tremendous scope of production by HP [1, 4]. But it has not been accepted as industrial technology yet, due to the lack of understanding. It is imperative to mention here that the traditional ironmaking processes primarily belong to metallurgical and chemical engineering specializations. In contrast, plasma in general and HP in particular, are interdisciplinary and involves a lot of physics and chemistry. It needs the attention of experts from these disciplines. Therefore, the physics of HP has been discussed first, followed by the chemistry of HP-iron ore reduction. Of course, the final application of the technology is for the production of iron, a major of metallurgical engineering, the details of ironmaking technologies are available in the literature [26-28].

### 2.1. Physics of Hydrogen Plasma

The traditional processes of reduction of metal oxides by gases (e.g., CO, $H_2$, etc.) are simple, and application of principles of physics is not required. In these processes, the analysis by metallurgical and chemical engineering is sufficient. But when the gas molecules are exposed to electrons or electromagnetic waves, they change their state to another state called plasma. Although plasmas are considered the fourth state of matter, they are nothing but excited gases. But analysis of plasma is a complex phenomenon, which needs experts from physics. It is a well-known fact that gas molecules are always associated with nucleus-nucleus, nucleus-electron and electron-electron interactions. There exist various attractions and repulsions between these species. In other words, gas molecules are always associated with some

**Table 1**

Quantities of reductants and products (in tonnes per 112 tonnes of Fe).

| Reaction | $H_2$ | $H_2O$ | C | CO | $CO_2$ |
|---|---|---|---|---|---|
| $Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O$ | 6 | 54 | | | |
| $Fe_2O_3 + 3C \rightarrow 2Fe + 3CO$ | | | 36 | 84 | |
| $Fe_2O_3 + 3/2C \rightarrow 2Fe + 3/2CO_2$ | | | 18 | | 66 |

electromagnetic interactions. Therefore, when energy is given to gas molecules by electrons or electromagnetic waves, the gas molecules' polarity interacts with the electromagnetic waves associated with electrons or electromagnetic waves. Due to this energy, the gas molecules get rotationally excited and then vibrationally excited (or rovibrationally excited), followed by dissociation and then ionization. In these states, the gases are called plasmas. For analysis of these plasmas, the physics of plasma is important. In fact, the importance of this vast area can be realized from the quote by NASA that “99.9 percent of the universe is composed of plasmas” [29]. The discussion on this vast area is beyond the scope of this review. However, HP has been discussed extensively by Murphy et al. [30, 31, 40-47, 32-39]. In this review, depending on the reduction of iron ore in liquid and solid-state, HP is divided into two types: (i) thermal or hot plasma and (ii) non-thermal or cold plasma, respectively. The difference between these two plasmas has been reported in Fig. 1.

### 2.1.1. Thermal or hot HP

In thermal or hot HP, the temperatures of all species present in HP are in thermal equilibrium, as shown in Fig. 1. This generally occurs at high temperatures. In this case, the reduction of iron ore is carried out in a molten state. Thermal plasmas provide the advantages of thermodynamic and kinetics, which is quite similar to using externally heated $H_2$ for the reduction of fine iron ore, like the suspension ironmaking technology [48, 49]. Due to the high temperature and excited active hydrogen species, thermal HP provides thermodynamic feasibility and quicker kinetics, respectively. This unique combination permits single-step iron production without any carbon footprint.

A thermal HP is formed from $H_2$ or an Ar-$H_2$ mixture. The thermal plasma can be produced in several ways. The examples are DC transferred arc, DC non-transferred arc, or inductively coupled RF discharge, etc. The $H_2$ molecules gain energy from the inelastic collisions with the electrons, which gained energy from the electric or electromagnetic field. After gaining energy, $H_2$ molecules become $H_2^*$, dissociate to H, and then ionize to $H^+$. These excited species partially recombine at the HP-$Fe_2O_3$ interface. This recombination generates a large amount of heat, supporting the endothermic reduction reaction of $Fe_2O_3$ [1,4].

Thermal HP processes used to reduce iron ore are of two types: (i) liquid–HP reduction and (ii) in-flight reduction. Liquid–HP reductions are somewhat similar to the conventional direct smelting processes. The in-flight HP reduction is similar to fluidized-bed reactors and suspension ironmaking technology [50]. The details of thermal plasma processes have been extensively discussed in an earlier publication [1].

### 2.1.2. Non-thermal or cold plasma

Non-thermal plasmas are plasmas where the heavy species and electrons are not in thermal equilibrium [51]. The difference in temperatures of heavy species and electrons is shown in Fig. 1. Due to this difference, they are also called non-thermal plasma or cold plasma. They are called cold plasma because the gas temperature remains such low that they can even be touched in a finger. In non-thermal or cold plasmas, although the electrons absorb energy from DC, AC, RF, MW, EM, etc., in the same manner as thermal plasma, the electrons are unable to transfer power to heavy species due to fewer numbers of collisions because of low pressure. Hence, the electron temperature remains higher than the temperature of heavy species. This temperature difference is observed in all non-thermal plasmas. Atmospheric pressure can also produce non-thermal plasmas, with plasma lifetime being very short. The short time doesn't permit the heavy particles to absorb energy from the electrons. Therefore, thermal equilibrium

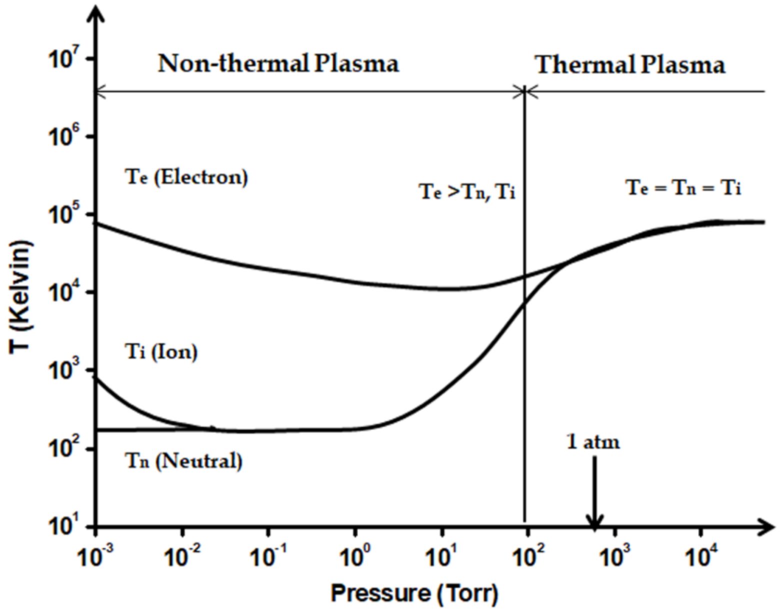

**Fig. 1** Difference between thermal and non-thermal plasma. The notations used: Electron temperature ($T_e$), vibrational temperature ($T_v$), rotational temperature ($T_r$), ion temperature ($T_i$), and gas temperature ($T_g$).

doesn't occur. Thus, in non-thermal plasmas, the electron temperature remains higher than the temperature of heavy species, as shown in Fig. 1. As shown in Fig. 1, non-thermal plasmas have the characteristics of several temperatures, i.e., electron temperature ($T_e$), vibrational temperature ($T_v$), rotational temperature ($T_r$), ion temperature ($T_i$), and gas temperature ($T_g$); typically, $T_e > T_v > T_r \approx T_i \approx T_g$ [1, 52, 53]. In many non-thermal plasmas, $T_e$ can attain 11600 K while keeping the $T_g$ at room temperature, hence can be touched in the finger. Although the non-thermal plasma indicates high electron temperature, sometimes to take advantage of both electron temperature and temperature heavy species (i.e., molecules, atoms, ions, etc.), moderate pressures are used. Moderate pressure incorporates high electron temperature, which gives rise to rovibrationally excited molecules. These $H_2$* molecules possess higher energy due to the energy stored in rotation and vibration of $H_2$, which increases the stored energy of the reactants, thereby decreasing the activation energy of the reaction. Moderate pressure also leads to increased collisions between the electrons and heavy species, giving rise to high gas temperature, directly related to chemical kinetics. Non-thermal plasma has already been used for several purposes such as thin-film deposition, etching of semiconductor, production of ozone, cleaning of gas, the surface of plastics modification, plasma displays, etc. Recently, the production of metals and alloys from various metal oxides and the mixtures of metal oxides or ores have been reported by Sabat et al. [1, 4, 6-10, 23-25].

### 2.2. Chemistry of Hydrogen Plasma Reduction

Thermodynamics and kinetics are the potential pathways for carrying a chemical reaction. In the current case, it is the reduction of iron ore by HP, discussed below.

#### 2.2.1. Thermodynamics of Hydrogen Plasma Reduction

The thermodynamic advantages of the excited species in HP have been illustrated in the Ellingham diagram (Fig. 2), which has been explained here. It is a well-known fact that the Ellingham Diagram predicts the spontaneity of the reduction reaction from the Gibbs standard free energy change (ΔG°). The feasibility of a reduction reaction is predicted from the negative value of ΔG°. The ΔG° is denoted by $\Delta G° = -RT\ln K$, where $K = 1/p_{O2}$, $p_{O2}$ is the pressure of oxygen. Therefore, ΔG° can be written as $\Delta G° = RT\ln p_{O2}$. The Ellingham diagram provides ΔG° ($= RT\ln p_{O2}$) as a function of $T$. Figure 2 estimates how the chemical equilibrium of iron oxides changes with $T$, $p_{O2}$, and composition, thereby providing information about the stability and spontaneity of reduction of iron oxides. The principle of the Ellingham diagram is that an element lying below in the diagram can reduce the upper metal oxides. The reduction reactions of interest here are the reduction stages of $Fe_2O_3$ by excited species present in HPs. As evident from Fig. 2, the molecular hydrogen line (i.e., $H_2$–$H_2O$ line) lies below the line of the $Fe_2O_3$ at all temperatures, and the $H_2$–$H_2O$ line lies below magnetite ($Fe_3O_4$) for temperatures above 900 K, indicating that $H_2$ can reduce iron oxides. However, in practice, it is difficult, due to constraints imposed by the thermodynamic and kinetics of $H_2$. The reduction of $Fe_2O_3$ by $H_2$ occurs in three steps: $Fe_2O_3 \rightarrow Fe_3O_4$, $Fe_3O_4 \rightarrow Fe_xO$, followed by $Fe_xO \rightarrow Fe$. $Fe_xO$ is called Wustite. Wustite is non-stochiometric, with x ranging from 0.83 to 0.955. For simplification, if x is assumed as x=1, the fractional oxygen removals for the three stages mentioned above are 1/9, 2/9, and 6/9, respectively. The following reactions can present the respective reduction reactions for the above three steps:

$$3Fe_2O_3 + H_2 = 2Fe_3O_4 + H_2O \quad \Delta G_1° < 0, \text{ all T} \qquad (1)$$

$$Fe_3O_4 + H_2 = 3FeO + H_2O \quad \Delta G_2° < 0, \text{ high T} \qquad (2)$$

$$FeO + H_2 = Fe + H_2O \quad \Delta G_3° > 0, \text{ all T} \qquad (3)$$

the overall reaction being:

$$Fe_2O_3 + 3H_2 = 2Fe + 3H_2O \quad \Delta G_4° > 0, \text{ ~all T} \qquad (4)$$

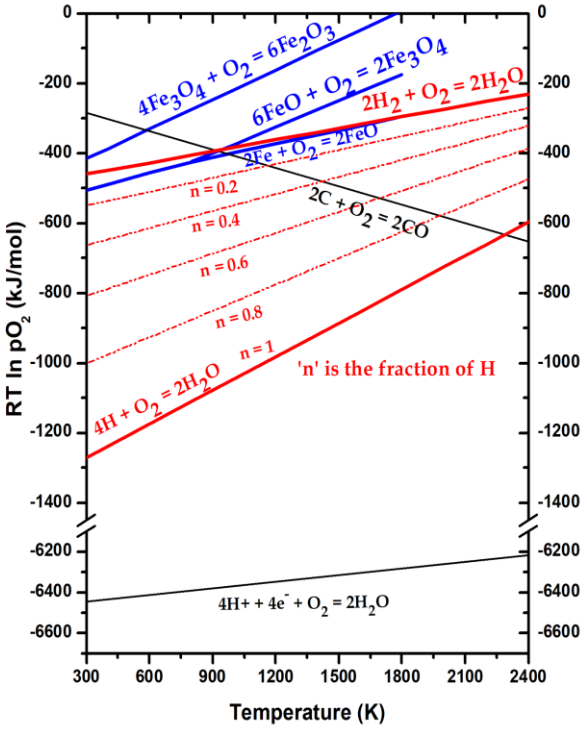

**Fig. 2** The Ellingham diagram of iron oxides, including the excited HP species [1]. Reproduced from [1] with permission from Springer.

The estimated ΔG° values of the above reactions are available elsewhere [1], are not being discussed here for simplicity. As evident from the ΔG° values of the above equations, the thermodynamically-feasible steps in iron oxide reduction are $Fe_2O_3 \rightarrow Fe_3O_4$ and $Fe_3O_4 \rightarrow FeO$, at high temperatures (i.e., above 900K). Therefore, these steps can be carried out by removing the kinetic barrier. The final step, $FeO \rightarrow Fe$, which accounts for the greatest fraction (6/9) of oxygen removal, is not only endothermic but also ΔG° positive, which strongly favors the reverse reaction $Fe \rightarrow FeO$, which is indicated by the Fe–FeO line's location below the $H_2$–$H_2O$ line in Fig. 2. An HP becomes important to move the $H_2$–$H_2O$ line downwards to a position below Fe–FeO line, i.e., to make FeO → Fe feasible.

When the $H_2$ is provided with sufficient energy ($E = h\nu$), $H_2$ converts to an HP containing $H_2^*$, H, $H^+$, $H^{2+}$, etc. The energy can either be supplied by thermal heating or electric discharges (i.e., AC, DC, MW, RF, etc.).

The reaction for HP can be represented by:

$$H_2(g) + h\nu = HP\ (H_2^*/2H/2H^+,\ etc.) \quad \Delta G_5^\circ >> 0 \qquad (5)$$

The thermodynamic coupling of Eqs. (3) - (5) gives the overall reaction for reduction of FeO by HP:

$$FeO + HP\ (H_2^*/2H/2H^+,\ etc.) = Fe + H_2O$$
$$\Delta G_6^\circ = \Delta G_3^\circ - \Delta G_5^\circ < 0 \qquad (6)$$

The $\Delta G_6^\circ$ is negative, indicating the feasibility of reduction even at low *T*, due to the presence of excited hydrogen species in HP. The detailed estimates of the decrease in ΔG° due to these excited species have been estimated in the earlier publication [1]. For example, the estimates of ΔG° for various atomic fractions of H (n = 0.2, 0.4, 0.6, 0.8, 1) are shown in Fig. 2. As evident from Fig. 2, the ΔG° decreases with the increase of n. A similar trend is there for other excited hydrogen species in HP. Due to this decrease in ΔG°, the reduction $Fe_2O_3 \rightarrow Fe_3O_4 \rightarrow Fe_xO \rightarrow Fe$ becomes favorable even at low temperatures. It has been reported that iron could be produced by HP even when the $H_2$ is at 573 K [6].

### 2.2.2. Kinetics of Hydrogen Plasma Reduction

As the reduction of $Fe_2O_3$ by HP starts, a product layer of Fe starts forming at the HP-$Fe_2O_3$ interface. The excited $H_2$ species present in HP are very small in size and possess a significant amount of energy for diffusion. Therefore, the diffusion of these excited species through the product Fe layer is unlikely the rate-limiting step. Therefore, the reduction rate depends on the nature of the excited hydrogen species present in the HP and their concentration adjacent to the surface of the iron oxide. For a reduction reaction to occur, the excited species present in HP and the $Fe_2O_3$ must first interact at the reduction interface to overcome the activation barrier of reduction. For instance, if the reduction of $Fe_2O_3$ by $H_2$ is considered, the rate coefficients can vary several orders of magnitude, depending on the internal energy of the reactants. However, in the case of HP, the excited species present in HP increase the internal energy of HP. This increase in internal energy of HP helps to reduce the activation barrier, therefore, lowering the activation energy of the reduction reaction. This lowering of activation energy results in faster kinetics of reduction of $Fe_2O_3$ by HP, in comparison to $H_2$ [1, 4].

Rajput et al. [6] carried out the solid-state reduction of $Fe_2O_3$ at different $H_2$ pressures, by $H_2$ and HP. Due to HP, the activation energy decreased from a value of 45 kJ/mol for reduction by $H_2$ to 20 kJ/mol for reduction by HP. This decrease in activation energy has been ascribed to the $H_2^*$ and other excited species present in HP. The HP constituted of 2 % H, 8 % $H_2^*$ ($\nu = 1$ level), and the remaining 90 % $H_2$. The HP energy estimated for this composition is 21.5 kJ/mol. Using this energy and ΔG° of the reactants and products, the activation energy for reducing $Fe_2O_3$ was calculated and shown in Fig. 3. The decrease in the activation energy for the HP (25 kJ/mol) agrees reasonably well with the calculated HP energy of 21.5 kJ/mol. This lowering of the activation energy by HP has also been reported for liquid $Fe_2O_3$-HP reduction [1].

Apart from HP's thermodynamic and kinetic advantages, the energy carried by these excited hydrogen species is effectively released at the reduction interface, causing local heating, favoring the reduction. Thus, volumetric heating is not required for reduction by HP,

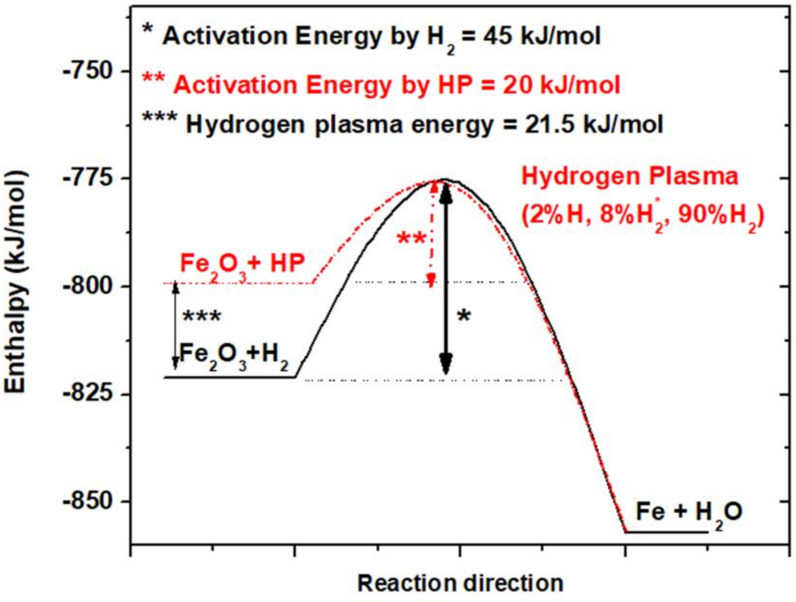

**Fig. 3** Decrease in activation energy for reducing $Fe_2O_3$ when $H_2$ is replaced by HP [1]. Reproduced from [1] with permission from Springer.

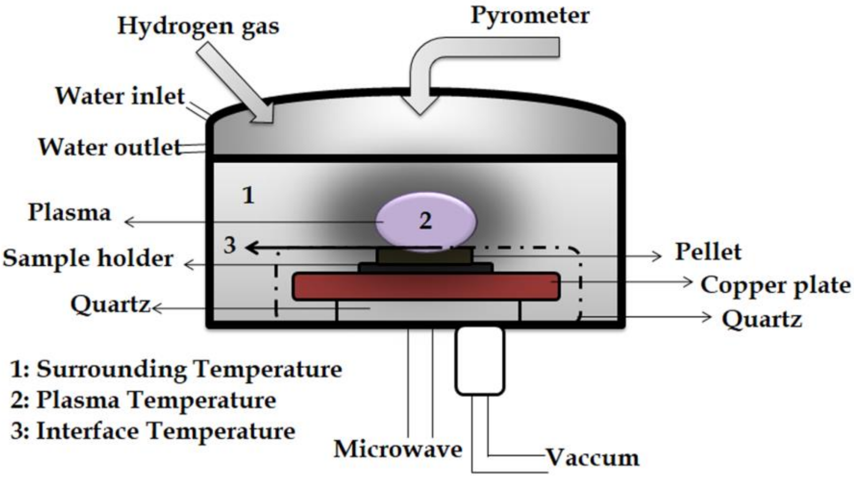

**Fig. 4** Microwave HP setup used by Sabat et al. [1, 4, 6-10, 23-25].

whereas volumetric heating is required for traditional reduction by $H_2$. The elimination of volumetric heating reduces the heat losses from the reactor, which reduces the cost. A cost-saving of 20 % has already been reported in liquid-state reduction of iron ore compared to the blast furnace ironmaking process [1,4]. The details of techno-economic feasibility have already been discussed in an earlier publication [1]. However, the work done so far on HP processes of solid-state reduction of iron ore has been discussed below.

## III. Developments so far

The reduction of metal oxides by HP has already been reviewed in an earlier publication [4]. The thermal or hot HP processing of iron ores has already been elaborated in an earlier extensive review [1]. The solid-state reduction of iron ore and others have been discussed here. The reduction of $Fe_2O_3$ by cold HP takes place at low temperatures in the solid state. Cold HP can be produced in several ways, as mentioned before. The cold HP has been used extensively by Sabat et al. [1, 4, 6-10, 23-25]. Sabat et al. used a simple microwave setup (similar to the domestic microwave) shown in Fig. 4.

The microwave plasma reactor incorporates a power supply up to 6000 W at 2.45 x $10^9$ Hz microwave generator to produce HP at high power densities. The high-frequency microwaves interact with the polarity provided by $H_2$ molecules inside the microwave oven to produce HP. The lump/pellet sample was placed on a molybdenum sample holder, which was in turn placed at the center of the reaction chamber within the plasma range. The microwave power and hydrogen flow rate were kept constant and monitored throughout the experiments. The temperature and pressure were properly monitored throughout the experiments. The reduction experiments were carried out for different periods till reduction goes to completion. The percentage reductions for each period were estimated from the weight loss measurements by digital weighing balance with accuracy 0.1 x $10^{-6}$ kg. Using this microwave setup, Sabat et al. [1, 4, 6-10, 23-25] reported the production of Fe from $Fe_2O_3$ [1, 6, 23], Cu from CuO [8], Co from $Co_3O_4$ [7], and alloys like FeCo alloy [9], CuNi alloy [10], CuCo alloy [25], etc., from the reduction of metal oxide mixtures. The details are available in the respective references. In these experiments, Sabat et al. could reduce lumps/pellets of size up to 15 mm, using microwave power in the range of 600 W to 1500 W, and $H_2$ flow rate in the range of 70 sccm to 500 sccm. The power ranges used in their investigations were below the power range required in domestic microwave ovens, generally used for cooking foods. Also, the sizes of the pellets were upto 15 mm. This size is being higher than the sizes of pellets/lumps used in traditional solid-state reduction processes for the production of sponge iron, etc., it opened up the possibility of mass-scale industrial production of metals and alloys from the reduction of their oxides/ores in solid-state by industrial processes (e.g., reduction roasting) using HP. Apart from microwave, this concept of HP reduction of iron oxide in solid-state can be utilized industrially by generating HP by other means such as DC, AC, RF, or any other EM. However, there have been almost negligible studies in solid-state reduction of iron ore by using HP produced from DC, AC, RF, or any other EM. Therefore, there is immense potential for research on the production of iron from the solid-state reduction of iron ore by HP. However, researchers and experts from physics, chemistry, and metallurgical engineering, should come forward to work together to make it a successful industrial technology.

## Conclusions

An overview of the physics and chemistry of solid-state reduction of iron ore using HP has been discussed.

The overall benefits of physics and chemistry of solid-state HP processing of iron ore can be summarized as follows:

1. HP can be produced easily by different methods, such as direct-current, alternating-current, radio-frequency, microwave, or any other electromagnetic field.
2. The study of the physics of HP is important for

the reduction of iron ore.

3. The chemistry of HP-iron ore reduction could be evaluated by thermodynamics and kinetics.
4. HP provides both the thermodynamic and kinetic advantages due to the excited species present in HP.
5. HP doesn't require volumetric heating. It only causes heating at the reduction interface, which is required for the reduction. Elimination of volumetric heating can reduce heat loss and cost.
6. The solid-state HP processing avoids the requirement for multiple processes in ironmaking and steelmaking.
7. Iron, not containing carbon, could be achieved in a single step.
8. The single-step without the involvement of carbon allows greater control over the process than the traditional processes using carbon.
9. This single-step can potentially eliminate the coke ovens, agglomeration plants, traditional blast furnaces, in future ironmaking technology.
10. The reduction of iron ore can occur even at room temperature.

The above advantages open a broad area of research on the production of iron from the solid-state reduction of iron ore by hydrogen plasma.

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**K. C. Sabat –** PhD in Extractive/Process Metallurgy. Faculty in Department of Materials and Metallurgical Engineering.

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Калі Чаран Сабат

# Фізика та хімія методу прямого твердотільного відновлення залізної руди водневою плазмою

*Національний технологічний інститут Маулана Азад, Бхопал, Індія*, kcsabat@gmail.com

На даний час залізо отримують із залізних руд, додаючи карбон із вугілля. Виробничий процес складається з багатьох етапів, що потребує великих капіталовкладень, обладнання для масштабного виробництва та продукує велику кількість вуглекислого газу ($CO_2$), відповідального за забруднення навколишнього середовища. Докладаються значні зусилля щодо заміни карбону воднем ($H_2$). Хоча $H_2$ є найсильнішим відновником, все ж, він має термодинамічні та кінетичні обмеження. Однак, такі термодинамічні та кінетичні обмеження можна усунути водневою плазмою (ВП). ВП містить молекулярно-атомні та іонні стани водню, що збуджуються в ротаційному середовищі. Усі вони сприяють термодинамічним перевагам, роблячи стандартну вільну енергію Гіббса більш негативною, що спричинює можливість відновлення оксидів заліза при низьких температурах. Окрім термодинамічної переваги, такі збуджені види збільшують внутрішню енергію ВП, що зменшує енергію активації, роблячи тим самим процес відновлення простішим та швидшим. Окрім термодинамічної та кінетичної переваги ВП, побічним продуктом реакції є екологічно безпечна вода. У цьому огляді обговорюється фізика і хімія відновлення залізної руди за допомогою ВП, наголошуючи на твердотільному відновленні залізної руди. Відновлення залізної руди за допомогою ВП має значний потенціал і є привабливим процесом відновлення.

**Ключові слова**: відновлення залізної руди, пряме відновлення заліза, губчасте залізо, процес виробництва заліза, воднева плазма, нетеплова плазма, фізика плазми, хімія плазми, термодинаміка плазми, кінетика плазми.