Chapter 2
Magnesium Smelting via the Pidgeon Process

Abstract At present, there are two main magnesium smelting methods: electrolytic method and reduction method. Compared with the electrolytic magnesium smelting process, the Pidgeon process has the advantages of simple and mature process flow, small investment, short construction period, multiple heat sources, good magnesium quality, low power consumption, and good utilization of coal, natural gas, heavy oil, gas and so on.

Keywords Pidgeon process · Magnesium smelting · Technological process · Facility

China is the world's largest producer of primary magnesium and has a magnesium smelting industry that is mainly based on the Pidgeon process. Magnesium smelting via the Pidgeon process is a process in which raw material (dolomite) is fed into a reduction tank that is externally heated by a reduction furnace, and then the calcined dolomite is thermally reduced to metallic magnesium using 75% ferrosilicon as a reducing agent in vacuum. The method is named after the inventor, L.M. Pidgeon, and has been applied for a long time; thus, it has been considered to be a classic silicothermic method for smelting magnesium. The Pidgeon process has a history of more than 70 years since its birth, and it has been used in industry in China for more than 40 years.

At present, there are two main magnesium smelting methods: electrolytic smelting and reduction smelting. Compared to electrolytic smelting, reduction smelting has the advantages of having a simple and mature process, requiring a small investment, short construction period, can use various heat sources, produces good quality magnesium, consumes a low amount of power, and can use energy sources such as coal, natural gas, heavy oil, and gas. In addition, China has the world's largest reserves of dolomite, which can be mined for more than one thousand years. This creates good resource conditions for the sustainable development of the Pidgeon process. However, the Pidgeon process also has problems, such as using a small sized reduction tank, having a low filling amount of a single tank, low thermal efficiency, and intermittent production, requiring high labor intensity, consuming high

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energy, and causing serious environmental pollution [1, 2]. The intermittent operation, low production capacity of a single tank, high energy consumption, and other issues limit the development of magnesium smelting via the Pidgeon process.

2.1 Processes in Magnesium Smelting via the Pidgeon Process

2.1.1 Introduction

Processes in magnesium smelting via the Pidgeon process include dolomite calcination, grinding and pelleting, and vacuum thermal reduction. The equipment that is mainly used for dolomite calcination is the rotary kiln. In a rotary kiln, calcined dolomite is the raw material, ferrosilicon is the reducing agent, and fluorite is a catalyst; these materials are weighed and mixed. After grinding, the mixture is pressed into spheres that are called pellets. The steps of grinding, batching, pelleting of calcined dolomite, and placing of the pellets into a furnace should occur as fast as possible (generally, in no more than 4 h). The pellets should be placed in sealed paper bags to avoid moisture absorption, which can reduce the activity of calcined dolomite and then reduce the yield of magnesium [3]. After that, the pellets are placed into a reduction tank and heated to 1200 °C. The inside of the furnace is evacuated to a vacuum level of 13.3 Pa or higher, and then magnesium vapor is produced. Magnesium vapor forms crystalline magnesium, which is also known as crude magnesium, in a condenser at the front end of the reduction tank. After the crude magnesium is refined via flux, commercial magnesium ingot is produced; commercial magnesium is refined magnesium.

The Pidgeon process uses silicothermic reduction to smelt metallic magnesium. There are two main chemical processes that occur in succession:

(1) Calcination of dolomite:

$$MgCO_3 \cdot CaCO_3 \overset{1100-1200\,^{\circ}C}{\rightarrow} MgO \cdot CaO(\text{calcined dolomite}) + 2CO_2 \uparrow$$

(2) Reduction:

$$2MgO \cdot CaO + Si(Fe) \overset{1200 \pm 10\,^{\circ}C}{\rightarrow} 2Mg + 2CaO \cdot SiO_2$$

The main technological process and basic route for the production of magnesium and magnesium alloys via the Pidgeon process have the same principles at home and abroad. The basic flow chart is as shown in the figure above. Differences in technological advancements and clean production levels of enterprises mainly include the levels of mechanization and automation, variations in fuel and energy consumption, and variations in the equipment that is used in each section. The current status of domestic and foreign magnesium smelting enterprises in these aspects is summarized as follows:

(1) There are three main methods to enhance the levels of mechanization and automation of the Pidgeon process. One method uses a microcomputer-controlled closed joint line consisting of batching, grinding, and pelleting. The second method uses mechanical equipment to accomplish slag-removal, tank cleaning, feeding, and magnesium extraction. The third method uses mechanized continuous casting. Advanced foreign enterprises can achieve all three methods, whereas the current advanced domestic enterprises only achieve two methods. Most magnesium plants in China cannot achieve one method, even achieve none at all. This means that the mechanization levels of these enterprises are still quite low, and corresponding improvement is urgently needed.

(2) Most magnesium plants in China use coal as fuel. The production of every 1 t of magnesium consumes 8–12 t of high-quality coal. In addition to wasting energy source and resources, this also emits a large amount of waste gas, causing serious environmental pollution. As seen from the advanced magnesium smelting enterprises at home and abroad that use clean energy, using clean energy is an effective way to enhance the level of magnesium smelting via the Pidgeon process. At present, some domestic manufacturers use coal-water slurry to greatly reduce the emission concentration of sulfur dioxide and nitrogen oxides that form during burning and to make the smoke and dust emissions reach Ringelmann black degree 0, which greatly improves the environmental impact of magnesium smelting via the Pidgeon process. Weienke Technology Company achieved good results with the use of coal-water slurry as a fuel in the production of magnesium smelting. For instance, the combustion efficiency of coal reached more than 98%, and the expected savings in coal would be approximate 20–30% [4].

(3) At present, in the order of advancing levels, the main calcination kilns (furnaces) that are used at home and abroad are sleeve-type shaft kilns, rotary kilns, and vertical kilns. The rotary kiln is the most widely used equipment for calcining dolomite. Regardless of the structure of dolomite, as long as the process conditions (reasonable kiln speed and feeding quantity) are carefully controlled, dolomite can be calcined to obtain good quality calcined dolomite. The utilization rate of raw material in a rotary kiln can reach over 90%; this is twice high as that of the shaft kiln, which has a utilization rate only 40–50% [5]. At present, it is common in Japan to use a rotary kiln in silicothermic magnesium smelting to calcine dolomite. Japan Tazawa Industry Co., Ltd., has two φ 2.5 m $\times$ 55 m rotary kilns for calcining dolomite that has high iron content, and the production capacity is 30,000 t/a [6]. Although a rotary kiln has good technical indicators, it is not the most advanced kiln type because of its high operating cost and low heat utilization rate. In recent years, the sleeve-type shaft kiln, which integrates energy-savings, environmental protection, and better performance, has been extensively used in Europe and Japan.

Practice indicates that the sleeve-type shaft kiln has simple equipment, convenient operation and maintenance, a better working environment, and excellent product quality; thus, it is a new type of kiln that has promising development prospects [7].

(4) The reduction process is the core of magnesium production, and the type of reduction furnace that is used greatly affects the advanced level of the process. A traditional magnesium reduction furnace has a long feed cycle, low efficiency, uneven feeding, and gaps in the tank's upper part; these characteristics result in unsatisfactory heat transfer. In addition, most traditional magnesium reduction furnaces lack a recovery device for waste heat; thus, high-temperature flue gas has been directly discharged into the air, causing serious waste in energy sources and serious damage to the environment [8]. The new dual-regenerative reduction furnace uses dual-regenerative combustion in air and with coal gas as fuel. The reduction furnace uses end-heating along the length of the furnace, and each heating point uses a semi-built-in heat storage burner; coal gas uses a two-position three-way reverse valve, and air uses a two-position four-way reverse valve to accomplish the reverse in direction.

The latest reduction technology in international magnesium smelting is vacuum smelting of metallic magnesium with internal electric heating. This technology heat reaction material from the inside part uses electricity as secondary energy. This can increase the reduction temperature, accelerate the reaction process, shorten the reduction cycle, increase thermal efficiency, and reduce energy consumption while avoiding pollution problems that are caused by the combustion of fuel. At the same time, the modified smelting method can increase the furnace capacity and increase the output of a single furnace. This process does not require expensive metal reduction tanks, and thus, the cost is less. In addition, the technology can be designed as a continuous production with automatic feeding and automatic discharging, both automatic feeding and automatic discharging cause this reduction of labor intensity [1, 9].

2.1.2 Raw Materials in Magnesium Smelting via the Pidgeon Process

The Pidgeon process uses dolomite as the main raw material, ferrosilicon as a reducing agent, and fluorite as a catalyst. After calculating, weighing, and batching, the reduction reaction of the raw material is completed in a reduction tank (furnace) to obtain crude magnesium. The ignition loss of dolomite in calcination is about 47%; this means 47% of dolomite decomposes into CO_2 gas, which is discharged into the air, not including the CO_2 that is produced during the heating of dolomite.

Dolomite is crushed in the mine to meet the required particle size, and it is stored in a plant's dolomite yard. Ferrosilicon and fluorite are directly stored in a plant's warehouse. All reserves are based on the amounts of materials that are required for production in half of a month. In silicothermic magnesium smelting, the calcination effect of dolomite directly affects the reduction yield of magnesium. Different types of kilns, different fuels, and different structural types of dolomite require different calcination conditions and result in different calcination effects. Because of different impurities and structures in dolomite, samples have different physical and chemical properties. At present, dolomite can be roughly divided into two categories: one is amorphous dolomite, which has a network structure; the other is a form of dolomite that has a hexagonal rhombus structure.

1. Amorphous dolomite with a network structure can retain the structural characteristics of dolomite after calcination. The particles of such calcined dolomite have large surface defects, and there are large cohesive forces between particles. Also, the amorphous dolomites are prone to deform under mechanical actions. The activity of amorphous dolomite in reduction is greater than that of dolomite that has a hexagonal rhombus structure.
2. Dolomite that has a hexagonal rhombus structure breaks easily, and it is easier to grind than dolomite that has a network structure, which is already finely ground. Also, dolomite that has a hexagonal rhombus structure does not preferentially adhere to the mill and its reactivity is lower.
3. The difference between the hydration activities of the two kinds of calcined dolomite is slight, but their activities in reduction are very different. These observations indicate that the hydration activity of calcined dolomite only represents its hygroscopicity and does not fully represent its activity in reduction. Generally, when hydration activity is higher, the activity in reduction is higher. However, for the same hydration activity, the activity in reduction is not necessarily the same because of the different dolomite structures.
4. Amorphous dolomite that has a network structure is selected. Because of its high strength and high hardness, the lumpiness of dolomite is easily ensured during crushing, that is, a low crushing rate is ensured.
5. Because of its low lattice energy, amorphous dolomite that has a network structure has a lower heat absorption capacity during thermal decomposition than dolomite that has a hexagonal rhombus structure. That is, the energy that is required for calcination is also lower, and there is less thermal cracking during calcination.

As seen from the above characteristics, dolomite that has a hexagonal rhombus structure after calcination has a high crushing rate and is easy to grind. Thus, it is not suitable for use in a shaft kiln or a mixed-load vertical kiln and is more suitable for use in a boiling furnace or a rotary kiln. The reason for this is that the calcined materials in shaft and mixed-load vertical kilns usually accumulate at the bottom discharge ports. Under the pressure of the upper material layer, calcined dolomite can easily become material that has a smaller particle size. This causes poorer air permeability, and the kiln can easily become blocked easily. This can even affect the normal operation of the entire kiln. However, this problem does not appear in rotary kilns and boiling furnaces.

Amorphous dolomite that has a network structure has high strength, high hardness, and low lattice energy. Thus, it has lower heat absorption during thermal decomposition than dolomite that has a hexagonal rhombus structure. Therefore, ideal calcination effects can also be achieved when such dolomite is calcined in shaft kilns and mixed-load vertical kilns. Such dolomite also exhibits good calcination effects in a rotary kiln, and this indicates that it is suitable for a wide range of furnace types. In summary, even though the same shaft kiln is used in current manufacturers, the fact that calcined dolomite has different activities in reduction is also a normal phenomenon because the structural characteristics of dolomite ore are different.

2.1.3 Processes in Magnesium Smelting via the Pidgeon Process

There are four main processes in smelting magnesium via the Pidgeon process: calcination, pelleting, vacuum thermal reduction, and refining.

(1) Calcination of dolomite: Dolomite is heated to 1100–1200 °C in a rotary furnace (rotary kiln) or shaft kiln to form calcined dolomite ($MgO \cdot CaO$). The specific process is as follows: After the calcined dolomite is crushed and screened, dolomite that has a particle size range of 10–40 mm is moved to the top silo of a vertical preheater using a large inclination belt conveyor. The materials in the silo are fed through a feeding pipe into the preheating box of the preheater. When the materials move slowly down into the preheating box, the dolomite is preheated to about 900 °C by the kiln's tail hot gas, which is at 1000–1100 °C. The rotary kiln provides a high-temperature heat source for the kiln through a burner that is installed in the kiln. High-temperature calcination causes dolomite to undergo thermal decomposition from $CaCO_3 \cdot MgCO_3$ (Scheme 1.2) at 1150–1200 °C to generate MgO and CaO, which are required for the reduction reaction.

$$CaCO_3 \cdot MgCO_3 \rightarrow MgO + CaO + 2CO_2 \uparrow \tag{1.2}$$

The calcined dolomite is cooled in a vertical cooler, where it is surrounded by cooling air that is provided by a secondary fan. The cooling air that is provided by a secondary fan reduces the temperature of that calcined dolomite that enters the cooler; the temperature of the calcined dolomite is cooled to below 100 °C, and the cooling air is correspondingly heated to over 700 °C so that it can be used as auxiliary combustion air for the combustion system. The cooled calcined dolomite is discharged by a vibrating unloader at the lower part of the vertical cooler, and it is transferred to a storage warehouse via a plate conveyor and bucket elevator.

The flue gas that comes from the pre-heater directly enters an electrostatic precipitator that is used to remove dust. The dust content of the exhaust gas after dust removal should be less than 80 mg/m^3 according to the relevant national requirements for environmental protection. The belt conveyor that is used for conveying dolomite is sealed with a belt corridor; the screening dolomite screening and the storage system used for the calcined dolomite are equipped with a pulsed bag filter. These measures effectively prevent environmental pollution that is caused by the storage and unloading of calcined dolomite and by the conveying and screening of dolomite.

(2) Batching and pelleting: Calcined dolomite, ferrosilicon powder, and fluorite powder are weighed, batched, ground, and pelleted according to the process requirements. The specific process is as follows: The preparation of pellets is conducted to prepare raw materials for the reduction process. The calcined dolomite that is produced in a rotary kiln is sent to pre-crushing equipment via the bottom unloading device of the stock. The unloading device is something such as a rod valve and a vibrating feeder belt conveyor. The crushed calcined dolomite is then sent to the silo. The ferrosilicon powder is also crushed and sent to the silo, and fluorite is used directly in the batching process. The three materials are mixed in the batching machine according to the required proportions, fed via a belt conveyor into a ball mill for grinding, and then pressed into pellets.

The calcined dolomite is sorted first, and a jaw crusher is used to crush ferrosilicon from the raw material storage yard to a particle size of about 10–20 mm. The calcined dolomite, ferrosilicon, and fluorite are mixed in a white calcined dolomite:ferrosilicon:catalyst fluorite ratio of 100:7.8:0.06. The mixture is placed in a ball mill and milled into a mixed powder of about 120 mesh (120 μm). A bucket elevator is used to lift the ground powder to a pellet presser, and then, the powder is pressed under a pressure of 9.8–29.4 MPa into an spheroid pellet that is about 40 mm. The pellets are sieved, and then, the pellets and powder that is smaller than 30 mm are returned to the pellet presser again. The qualified pellets are conveyed to the reduction workshop.

(3) Reduction: The pellets are heated to 1200 ± 10 °C in a closed reduction tank. To prevent the reduced Mg from being oxidized again under high temperature conditions, the reduction tank needs to be evacuated under a vacuum level of 13.3 Pa or higher. Magnesium oxide is reduced to magnesium vapor at this temperature and under this vacuum for 8–10 h; the magnesium oxide becomes crude magnesium after condensation. Specifically, the pellets are placed in a reduction tank of a reduction furnace and reduced by silicon in ferrosilicon to form metallic magnesium under vacuum. The high-temperature section of the reduction tank is made of heat-resistant steel, and the condensing section that extends out of the protective outer layer is welded with ordinary seamless steel pipes and placed horizontally in the reduction furnace, forming a structure that has “one furnace with multiple tanks”.

The prepared pellets are placed in the reduction tank, which has a fire shield. The tank mouth is sealed, a jet pump is started to generate a vacuum, and the entire vacuum system is maintained below 5 Pa. The reduction furnace uses coal gas from the generating furnace as fuel. When the pellets are heated to 1150–1200 °C, the pellets are in their molten state. Under the catalysis of fluorite, silicon atoms in ferrosilicon reduce the magnesium ions of MgO to metallic magnesium. Metallic magnesium sublimates at high temperature into magnesium vapor. The vapor is cooled at the head region of the reduction tank and then condensed into solid crude magnesium. The general reaction time is 12 h. After the MgO in the pellet is completely reduced to metallic magnesium, the cover of the reduction tank is opened, and the metallic magnesium is removed using a hydraulic press. The remaining waste slag in the reduction tank is manually removed and poured into a fire pit; water is sprayed on the waste residue to prevent dust from rising. The main chemical reaction in silicothermic reduction is shown in (Scheme 1.3) [10]:

$$2\mathrm{MgO} + 2\mathrm{CaO} + 2\mathrm{Si(Fe)} \overset{1190-1210\,^{\circ}\mathrm{C}}{\rightarrow} 2\mathrm{CaO} \cdot \mathrm{SiO_2} + 2\mathrm{Mg} \uparrow \tag{1.3}$$

The reduction process is an intermittent operation. The specifications of the reduction tanks that are used by different magnesium producers are different. Accordingly, the amount of feeding material, magnesium output, and the reduction cycle are different. The general cycle is 8–12 h long. There are also large tanks that have a reduction cycle that is 24 h long. At the beginning of a reduction cycle, the pellets are first placed in the reduction tank, and this position corresponds to the region for the reduction reaction. A heat shield is then used to block the heat radiation of pellets, and a magnesium crystallizer and alkali metal trap are installed in turn. Finally, the end cover is fixed, and the system is evacuated.

To obtain dense crystalline magnesium, the reduction is carried out under a vacuum less than 10 Pa. The temperature in the region of the reduction reaction is maintained at 1473 K. At this temperature, the $\mathrm{MgO} \cdot \mathrm{CaO}$ in the pellets is reduced to metallic magnesium by silicon in ferrosilicon. The generated metal magnesium vapor escapes to the crystallizer. The vapor then crystallizes while the generated alkali metal vapor condenses in the alkali metal trap and then separates from the crystalline magnesium. After reduction, the vacuum unit is turned off, and the vacuum system is connected to the atmosphere. The reduction tank is opened, and the alkali metal trap, magnesium crystallizer, and heat shield are removed. The slag is cleaned and the crystallized magnesium is removed for the subsequent refining.

(4) Refining ingot casting: Crude magnesium is heated and melted. Then, it is refined via flux at a high temperature of about 710 °C, and the refined magnesium is cast into ingot, also known as refined magnesium.
(5) Acid-washing: The surface of magnesium ingot is cleaned with sulfuric acid or nitric acid to remove surface inclusions, and the surface is made to be more shiny.

2.1.4 Factors Affecting the Reduction of Magnesium

When magnesium is smelted via the Pidgeon process, vacuum thermal reduction is the core process and is also the process by which magnesium is obtained. The quality of this process directly affects the output of crude magnesium. Therefore, the factors that affect the reduction process must be addressed:

1. The effects of calcined dolomite's activity, ignition loss, and impurity content

The activity of calcined dolomite refers to the amount of active MgO in calcined dolomite and can be measured using volumetric measurements (YB/T105-2005). When the activity of calcined dolomite is between 30 and 35%, the magnesium output increases significantly. When the ignition loss of calcined dolomite is greater than 0.5%, it has a serious effect on the vacuum in the tank. At the same time, this also causes the formed H_2O and CO_2 to react with magnesium vapor and decreases the reduction rate. In addition, when the contents of other impurities, such as SiO_2 and $A1_2O_3$, are too high, they form slag with CaO and MgO, and this correspondingly reduces the activity of MgO. Meanwhile, impurities cause nodules in slag and then cause difficulties in operation. When the total amount of K_2O and Na_2O in the pellets is greater than 0.15%, oxidation-combustion loss occurs if there is metal magnesium in the reduction tank. This thereby reduces the actual yield of magnesium.

2. Effect of the reduction capability of ferrosilicon

Production practices have verified that the yield of magnesium is too low if ferrosilicon with a silicon content less than 50% is used. When ferrosilicon that has a silicon content above 75% is used in reduction, the magnesium output increases significantly. However, when the silicon content in ferrosilicon is further increased, the increase in magnesium output is not significant; thus, it is economical and reasonable to use ferrosilicon that has a silicon content above 75% to reduce calcined dolomite. Wang Yaowu et al. [11] invented an aluminum-containing reducing agent for use in magnesium smelting; they used aluminum ingots, waste aluminum, and aluminum alloys as raw materials to prepare the aluminum-containing reducing agent for magnesium smelting. The magnesium smelting process uses the same equipment as that used in the current Pidgeon process. Feng Naixiang et al. [12] invented a vacuum magnesium smelting method that uses a silicon-magnesium alloy as a reducing agent. The reduction reaction was carried out at 1000–13,000 °C, and a vacuum pressure less than 80 Pa was applied; this can greatly reduce the energy consumption of magnesium production and substantially increase the production efficiency. Han Fenglan et al. [13] invented a boron-containing mineralizer to replace fluorite. The amount of mineralizer used is less than that of fluorite, thereby reducing the environmental pollution of fluorine-containing compounds. Similarly, Han Fenglan et al. [14] used rare earth oxides as mineralizers to obtain modified magnesium slag that had better gelling activity. The application of such magnesium slag in cement and concrete blocks increases the addition ratio and enhances the utilization rate of magnesium slag. In terms of the reduction step, Dong Jiayu et al. [15] invented a new reduction step to modify the Pidgeon process. Materials were stirred via rotation of a reduction tank, so that the intermediate materials can be heated. This solves the problem of high vapor pressure in the materials' reaction. Thus, the reduction time is shorter, and the reduction temperature is lower.

3. Effect of component ratio

Specific production practices have proven that with an increase in the molar ratio of Si/MgO, the yield of magnesium increases accordingly while the utilization rate of silicon decreases. To make a reasonable use of the reduction ability of ferrosilicon and to effectively increase the yield of magnesium, the Si/MgO ratio should be maintained in the range of 1.8–2.0. Meanwhile, the component ratio should be adjusted over time according to variations in the composition of the feed material and the content of ferrosilicon during the production process.

4. Effects of reduction temperature and vacuum degree

In the normal production process, the reduction temperature should be controlled to be within the range of 1100–1150 °C, the furnace temperature should be controlled to be within the range of 1150–1200 °C, and the vacuum degree should be controlled to be between 10 and 15 Pa. If the reduction temperature is further increased, it has a great impact on the lifetime of the reduction tank and the furnace, although the reduction rate and recovery rate of metallic magnesium can be increased. Therefore, a further increase in reduction temperature should be considered in a more comprehensive manner.

5. Effect of mineralizer

In the process of silicothermic reduction, according to the production conditions of dolomite and the reduction tank, 1–3% CaF_2 is added to the pellet materials for the purpose of accelerating the reaction between SiO_2 and CaO to form $CaSiO_3$, which then increases the reduction rate and the output.

6. Effect of the particle size of the material

The particle size of calcined dolomite and ferrosilicon affect the formation of pellets as well as the reduction process of magnesium. Fine and uniformly-mixed pellets increase the contact area between calcined dolomite and ferrosilicon, and this subsequently accelerates the reaction and increases the reduction rate. However, when pellets are too fine, they are prone to thermal fracture and pulverization, and this affects the normal process of the reduction reaction.

7. Effects of density and strength of pellets

Increasing the pelleting pressure can enhance the strength and density of the pellets. These characteristics can thus reduce crushing, increase the loading amount, enhance the thermal conductivity, accelerate the reaction, increase the output, and increase the actual yield of magnesium. The required density of the pellets is in the range of 1.9–2.1 g/cm^3; the strength of the pellets must meet the requirement that when a pellet falls freely from a height of 1 m to a cement floor, it breaks into 3–4 pieces without producing powder [10]. Wu Yong [16] pressed material into a honeycomb coal-like briquette to replace the walnut-like pellets that are used in the traditional process. This invention changed where briquettes are placed in filling the tank, increased the filling coefficient, and increased the single-tank filling. As a result, the heat energy distribution in the reduction tank is improved, the thermal efficiency is improved, and the output of a single tank is increased.

2.1.5 By-Products in Magnesium Production

1. Waste heat utilization of magnesium slag

After decades of development, especially with the application of regenerative reduction furnaces in the past ten years, the energy consumption of magnesium production has been reduced from 10 to 4–5 t with standard coal for 1 t of magnesium [17, 18]. However, if the energy consumption of producing ferrosilicon is included, the total energy consumption of the Pidgeon process is still as high as 8 t of standard coal. The unit energy consumption even exceeded that of metal aluminum production and was one of the nonferrous metallurgical industries that had the highest unit energy consumption [19]. The main reason for this is the low reduction rate of MgO during the reduction process, which was about 80% and has not been greatly improved upon to date [20, 21].

Recycle of waste heat generated via dolomite calcination: The dolomite calcination process consumes a lot of energy and produces high-temperature flue gas. If the flue gas is directly discharged into the air, the energy contained in the high-temperature flue gas is wasted. This energy waste can be reduced by recycling waste heat that is generated via dolomite calcination. Recycling waste heat can be implemented in the following ways: (1) High-temperature exhaust gas can be introduced into the vertical preheater to preheat the dolomite, and this can shorten the heating time of dolomite in the rotary kiln and reduce the amount of coal gas that is used. (2) High-temperature exhaust gas is used to generate electricity, and the generated electricity is used in various production projects or is connected to the grid. (3) A waste heat-recycling boiler can be added to collect the heat of flue gas and then to produce hot water for heating in winter or for use in daily life. The temperature of the final exhausted flue gas is greatly reduced, and it can be discharged into the air after dust is removed using cloth bags [22].

The temperature of the magnesium slag when it is just removed from the reduction tank is very high (at around 1200 °C), meaning that it contains a huge amount of energy. However, most magnesium enterprises have not taken measures to use this energy, and so the heat is wasted. Therefore, recycling waste heat of high-temperature magnesium slag effectively reduces the energy consumption in producing 1 t of magnesium. A recycling device for waste heat generated by magnesium slag can be developed to blow cold air upward from the bottom of the recycle chamber for magnesium slag, and high-temperature magnesium slag will simultaneously fall from the top of the chamber. The full heat exchange between magnesium slag and air produces high-temperature air, which can be used to preheat material or produce domestic hot water.

2. Recycling and using magnesium slag

Magnesium smelting produces a large amount of magnesium slag. "For every 1 t of crude magnesium produced by an enterprise, 6–10 t of magnesium slag would be produced." [23] Magnesium slag has extensive applications, such as producing cement, concrete expansion agents, and paving materials. The Jingfu coal chemical enterprise in Fugu, Shaanxi uses magnesium slag and coke dust to produce nonburning bricks and obtained satisfactory results. This practice uses magnesium slag and also enables the enterprise to have a new source of profits [22].

2.2 Main Equipments in Magnesium Smelting via the Pidgeon Process

2.2.1 Preheating Furnace

The top of the preheater is generally equipped with a silo, and the silo is equipped with a level gauge to control the height of the material layer. There is a slip pipe between the silo and the preheater body to move dolomite into the preheater and to seal the material to prevent cold air from entering the preheater. After the raw materials are moved into the preheater, they flow under the action of high-temperature exhaust gas released by calcination and move in the direction opposite to the feed direction. The reverse flow carries out a sufficient heat exchange to uniformly preheat the materials. Various hydraulic push rods are used to push the preheated material into the kiln, and this can shorten the calcination time in the kiln. After the heat exchange, the flue gas can be processed by the dust collector and then discharged into the air.

2.2.2 Calcination Furnace

At present, the main equipment that is used for calcining dolomite includes the rotary kiln, shaft kiln, fluidized bed furnace, gas-fired vertical kiln, and composite vertical kiln.

(1) Rotary kiln

The rotary kiln is the key equipment that is used in preparing active dolomite. The rotary kiln is mainly composed of a transmission device, supporting device with a roller, supporting device with a damper, barrel, kiln head, kiln tail, sealing device, kiln head cover, and combustion device. The barrel is a rotary part that is heated during the calcination of dolomite; it is made of a coiled and welded high-quality steel plate and is inclined to have a certain angle. The entire kiln body is supported by a roller, and there is a mechanical or hydraulic gear damper that can be used to control the axial displacement of the kiln body. The transmission device causes the barrel to rotate at the required speed using a gear ring that is in the middle of the barrel. In addition to the main drive, which is driven by a DC or variable-frequency speed-controllable main motor, the transmission part is also equipped with an auxiliary transmission device to ensure that the kiln body rotates slowly and prevents the kiln body from deforming when the main drive power is interrupted during installation and maintenance. To prevent cold air from entering the barrel and to prevent the overflowing of flue gas and dust from the barrel, a reliable kiln tail and kiln head composite with fish scale-like sealing devices are installed at the feed end (tail) and discharge end (head) of the barrel. In this design, a kiln with a larger diameter and shorter length is used; this reduces the vertical movement range of the kiln body, prolongs the ring-formation period inside the kiln, and saves space.

The particle size of dolomite ore is small (5–25 mm). When the kiln is rotated, the material inside the kiln rolls fully, and this intensifies the heat transfer via radiation. The materials are uniformly heated, and the calcination is complete. The calcination temperature is easy to control. When the rotary speed of kiln and the feed rate are reasonable, calcination produces calcined dolomite that has excellent activity and lower ignition loss. The raw material utilization rate of a rotary kiln (90%) is twice as large as that of a shaft kiln (40–50%). Considering the reduction in production costs, the rotary kiln is the most ideal choice of equipment for magnesium plants. Therefore, most domestic magnesium smelting manufacturers that use the Pidgeon process use a rotary kiln to calcine dolomite. At present, the largest domestic rotary kiln for calcining dolomite is Baosteel's φ 3 m $\times$ 70 m rotary kiln, which has a daily output of 600 tonnes of calcined dolomite. The smaller rotary kiln has dimensions of 1.2 m $\times$ 26 m and a daily output of 18 tonnes of calcined dolomite.

Previous production practices have proven that, the calcination effect of a rotary kiln is very remarkable as long as the process conditions are well controlled regardless of the structure of the dolomite. The calcined dolomite that is produced using a rotary kiln has higher activity, along with a higher extraction rate of magnesium and higher utilization rate of silicon. The calcined dolomite that is produced using other furnace types has high activity, and the extraction rate of magnesium and utilization rate of silicon are also relatively high. The activity of calcined dolomite produced using other furnace types is relatively poor.

(2) Shaft kiln

A shaft kiln is stationary vertical calcination equipment. At present, most domestic small-scale magnesium smelting plants that use the silicothermic method use this type of kiln; this particularly true of individual enterprises in townships and villages. Most of the magnesium plants that have an annual output of 200–300 tonnes use a shaft kiln as their calcination equipment. The shaft kiln is characterized by its simple structure and low one-time investment. Compared with the rotary kiln, the shaft kiln has lower output and larger loss and produces lower activity calcined dolomite. Because the cooling time of calcined dolomite is longer in a shaft kiln, the calcined dolomite easily absorbs water and is easily pulverized. There are other problems, such as a low temperature calcination zone, insufficient calcination, low thermal efficiency, large layer resistance, and a calcined material that has a wide distribution of particle size (60–150 mm). Therefore, the technology for calcining dolomite in the shaft kiln needed to be modified. In addition to improving the operation and selection of raw materials, other modifications include improving the structure of the furnace, increasing the mechanization level, using coal-fired machinery to reduce labor intensity, and using a semi-gas external combustion chamber with a bottom discharge. For current small magnesium plants, the rational use of shaft kilns is still essential.

(3) Fluidized bed furnace

In recent years, fluidized calcination is a new technology that has been developed in China for calcining dolomite. The fluidized bed furnace has been used by foreign enterprises to calcine dolomite lime, and it is effective. Because of the low investment in equipment, large production capacity, and lower energy consumption than rotary kilns, domestic research has begun to adopt the fluidized calcination equipment and process. The basic process of fluidized calcination is as follows: Crushed small dolomite particles are added into the furnace, and combustion gas is introduced into the furnace. The materials are fluidized and stirred in the furnace to make the temperature of each material layer uniform and to efficiently decompose dolomite. During the calcination (which lasts about 15 min), the calcination temperature must ensure that there is no under firing or overfiring and that dolomite is completely decomposed. The decomposition temperature of $MgCO_3$ in dolomite is in the range of 734–835 °C and that of $CaCO_3$ is in the range of 904–1200 °C. CaF_2 is added to accelerate the decomposition of dolomite. The calcination time of dolomite is closely related to the calcination temperature and the particle size of dolomite. Fluidized bed calcination is a rapid calcination process at high temperature.

The calcination of dolomite in a fluidized bed furnace is ideal, and the investment is low. The calcination of dolomite in a fluidized bed furnace is new technology that is worth promoting, and it is especially suitable for medium-scale and small-scale magnesium plants.

2.2.3 Vertical Cooler

The high-temperature materials that are calcined in a rotary kiln flow into a vertical cooler that is encased by refractory materials. The cooler can be divided into four cooling-discharging regions, and the discharging speed within each region can be individually controlled according to the temperature of the materials. Center blast caps and cooling caps in each compartment are evenly distributed within the cooler. A blast cap is connected to a fan through a pipe. The material layer is stacked on and covers the blast cap, scattering down along the bus bar of the blast cap. The material makes reverse contact with cold air that is released through air holes in each layer of the blast cap, thereby completing the heat exchange. When the material is cooled to a temperature that is 80 °C higher than ambient temperature, the material is gradually discharged from the cooler under the action of a vibrating unloader. Heated air enters the rotary kiln directly from the kiln head cover and participates in combustion as secondary air. There are no moving parts in the cooler, and thus, it has a simple structure, good cooling effect, and less equipment maintenance.

2.2.4 Reduction Resort

In magnesium smelting via the Pidgeon process, the magnesium reduction tank is a very important component in the production process and is a consumable part. At present, the reduction tank is usually cast from high chromium-nickel alloy steel. The tank has a shorter service life (generally no more than 2–3 months), and the cost of the tank accounts for about 25% of the price per tonne of magnesium. The high cost of the reduction tank is a problem that magnesium smelters are concerned about and cannot do anything about. Therefore, producing a reduction tank that is higher quality and has a longer service life is of great significance for reducing the cost of magnesium production and for improving the economic benefits of enterprises [24] (Fig. 2.1).

The reduction furnace consumes huge energy. The traditional reduction furnace is the core equipment for silicothermic smelting of magnesium, and it is an externally-heated flame reverberatory furnace. A single row of reduction tanks is arranged horizontally in the reduction furnace. There are two dimensions of reduction tanks (φ 339 mm $\times$ 33 mm $\times$ 2000 mm and 370 mm $\times$ 35 mm$\times$ 2000 mm), and the amount of pellets in each tank is in the range of 165–180 kg. The reduction tank is made of thermally-resistant steel alloy. The reduction reaction of the pellets that are packed in the reduction tank occurs under vacuum (<5 Pa) and at a high temperature such as 1200 °C. Early reduction furnaces directly burned coal, and the furnace is manually fired. The consumption indicator of coal in the reduction is about 8 tce/t Mg; some furnaces have also used hot coal gas as fuel without preheated air, and the coal consumption in this reduction has been as high as 10 tce/t Mg or more.

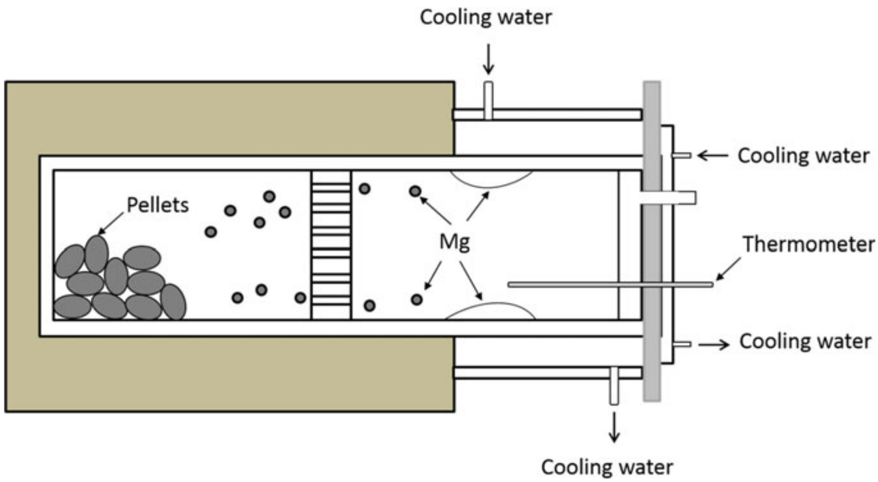

Fig. 2.1 Schematic diagram of reduction tank

From 1998 to 2004, the reduction furnace was changed from a single row of tanks to double rows of tanks. Meanwhile, a heat exchanger with metal dividing walls was used to preheat the air. The temperature used to preheat the air was about 450 °C, and the consumption indicator of coal in reduction was reduced to 6 tce/t Mg. At the same time, the waste heat from the flue gas after preheating the air is used to produce steam, and this can be used to drive the jet vacuum pump, thereby reducing the power cost of the vacuum. From 2004 to 2010, a regenerative magnesium reduction furnace with a horizontal tank was gradually developed and improved. The regenerative reduction furnace uses high-temperature technology to preheat air, and this can use clean energy such as low-calorific value fuels. Meanwhile, this furnace can be used to fully recover waste heat from the flue gas, greatly save energy, reduce consumption, reduce pollution emissions, and increase the output of the furnace and kiln [25, 26]. Therefore, heat storage technology has been rapidly promoted and applied in domestic reduction furnaces used for smelting magnesium. Also, the use of heat storage technology in the reduction furnace is becoming mature. The regenerative reduction furnace can preheat air and fuel to a temperature that is close to the working temperature of the furnace, and so it creates a uniform temperature in the furnace. As a result, the heating efficiency of the regenerative reduction furnace is much higher than that of traditional reduction furnaces and its coal consumption is reduced to 3.35 tce/t Mg; the coal consumption of a reduction furnace that has a more reasonable structure can be reduced to 3.0–3.1 tce/t Mg. However, compared to the theoretical energy consumption of 0.62 tce/t Mg in the reduction process, the energy consumption of the current reduction furnaces are still relatively high [27]. Table 2.1 compares the technical indicators and process parameters of a regenerative reduction furnace and a traditional reduction furnace.

Table 2.1 Technical indicators and process parameters of a regenerative reduction furnace and a traditional reduction furnace

Indicators and parameters	Traditional reduction furnace	Regenerative reduction furnace
Fuel consumption for producing a tonne of magnesium (t, using coal as fuel)	7	3
Temperature inside furnace (°C)	1200–1270	1200–1220
Material-magnesium ratio	6.8	6.2
Heating rate (C/min)	60	30
Cycle time (h)	11	10.5
Flue gas temperature (°C)	900	<150
Discharged volume of harmful gas (Bm^3/h)	2500	Trace amount
Preheated temperature of air and coal gas (°C)	N/A	1000

In 2011, Qu Tao et al. [28] used a semi-continuous feeding system to change the magnesium smelting reduction furnace to a semi-continuous vacuum-induction reduction furnace. The reduction region was heated via the vacuum induction method, and the reduction slag was discharged from the lower part of the reduction tank. This new design separated the reaction vessel from the device used to collect the magnesium vapor. This replaces the traditional discontinuous reduction process, increases output, and reduces energy consumption.

At present, most magnesium plants use horizontal reduction tanks. The horizontal reduction tanks cannot use the force of gravity on raw materials to drive automatic feeding, and so, manual feeding is generally used. In addition, the force of gravity on waste slag cannot be used to automatically remove slag, and so, manual slag removal is also required. Although some enterprises have achieved automatic slag removal from horizontal tanks, the failure rate of slag-removal equipment is relatively high, and magnesium slag is prone to remain in the reduction tank. After vertical tank technology was introduced, a reduction tank that is positioned vertically in the furnace makes feeding and slag discharge very convenient, and it easier to achieve automatic feeding and automatic slag discharge. These characteristics are conducive to the application of artificial intelligence and automation to production and can also reduce the cost of manual slag removal [22].

After 2010, some enterprises and scientific research institutes carried out a lot of research and development on energy savings and reduction of energy consumption in reduction furnaces. Technologies such as mechanized slag cleaners, vertical magnesium reduction furnaces, and composite magnesium reduction furnaces have been successively developed and tested in the magnesium industry. This new equipment has achieved good energy-savings and emission reduction effects.

1. Mechanized slag removal and vertical reduction furnace for magnesium smelting

To reduce operating time of reduction furnaces, reduce ineffective heat loss, and reduce labor intensity of workers, some magnesium smelting enterprises and scientific research institutes have developed mechanized slag cleaners for reduction furnaces with a horizontal tank. This has mainly included spiral slag cleaners and pneumatic slag cleaners. When a slag cleaner is used, operating a mechanized slag cleaner is difficult and has a higher failure rate because of the low one-tank output of the horizontal tank, more tank bodies being used, the tank body length being nearly 3 m (the high temperature section is 2 m long, and the vacuum section is nearly 1 m long), deformation at high temperatures, material sticking to the tank and forming a glaze, and other problems. Moreover, it is difficult to achieve mechanized feeding with a horizontally-placed reduction tank, and so, mechanized operation cannot be fully achieved. For this reason, the magnesium industry began to develop a reduction furnace that uses a vertical reduction tank.

Magnesium smelting technology that uses a vertical tank has a tank that is positioned upright in the furnace. Compared to a reduction furnace with a horizontal tank, the vertical magnesium smelting reduction furnace has the following advantages [29]:

Magnesium output of a single tank is increased. Raw materials in the vertical reduction tank are filled fully and uniformly. The pellets are in contact with the inner wall of the reduction tank, and this causes the pellets to be uniformly heated. Meanwhile, a more uniform temperature field is distributed in the tank, and this is favorable for the reduction reaction. (2) The cycle of reduction production is shortened. Under the action of gravity, the transfer of pellets and crude magnesium and automatic discharge of slag are achieved; this shortens the auxiliary operation time of reduction production and reduces ineffective heat loss caused by the reduction furnace. (3) Utilization of waste heat that is generated by reduction slag is strengthened. Slag in the vertical reduction tank is automatically discharged to the slag box under the action of gravity. The waste heat of high-temperature slag is recycled through a heat exchange device, and the recycled heat is used to preheat the reduction material and to achieve the use of the waste heat of the slag material. (4) The service life of the reduction tank is extended. The reduction tank stands upright in the heating furnace body, and its placement direction is consistent with the direction of gravity. Thus, the force on the tank is uniform, and the reduction tank does not easily deform; a rapid change in the surface temperature is alleviated through mechanized feeding, slagging, and preheating of material, and this extends the service life of the reduction tank. (5) Working conditions are improved. Mechanization of taking magnesium, adding materials, and discharging slag improves working conditions and reduces labor intensity. After several years of technology development and production practice, it has been shown that the reduction energy consumption of the vertical tank reduction furnace can be reduced to 2.4–2.5 tce/t Mg. Although erecting the reduction tank does not fundamentally solve the problems of the low heat transfer efficiency of the silicothermic method and the “chimney effect” of the vertical tank exacerbates the working environment. However, compared to the horizontal tank reduction furnace, the vertical tank reduction furnace is more conducive for large-scale and mechanized development and has greater research and promotion application value.

Among them, a new magnesium smelting technology that uses a composite vertical tank has been developed by a magnesium-based technology and materials research and development team that is jointly associated with Zhengzhou University, Xi'an Jiaotong University, and other institutes. Through more systematic thermochemical research, they correct, supplement, and improve the relevant basic theories of the silicothermic method used in magnesium smelting. Their work has Aimed at the problems of using a horizontal tank or vertical tank in the silicothermic method, and they have developed an innovative new type of magnesium smelting process that uses a composite reaction furnace as the core equipment. In addition, a steam generator that uses crystallization heat and a recycling device used for waste heat of reduction slag are key equipment. The new method is a refining-free "two-step" magnesium smelting process that uses a composite vertical tank [29]. The large-scale composite vertical tank consists of three independent parts: a crystallizer, reducers, and a slag cleaner. The longitudinal and radial directions are composed of multiple independent components with perfect structure and complete functions; the combination forms a composite structure. The magnesium output of each composite vertical tank can reach 800 kg/d, and the service life can reach about 300 d. There are 50 composite vertical tanks in a reduction furnace. Feeding, slagging, and magnesium discharging are all mechanized. The flue gas and fuel system are self-balanced, and their operations are automatically controlled. Thus, the reduction furnace can be used for large-scale and automated production. This technology has been built and put into production with a output of 12,500 t/a. In actual operation, the comprehensive energy consumption of an entire plant that uses this technology is about 3 tce/t Mg, and the reduction time is about 6 h, which is only 2/3 of that used in the Pidgeon process. A single crystallizer can produce approximately 200 kg of magnesium at a time, and the purity of the crystallized magnesium is higher than 99.8%. These observations indicate that the magnesium smelting process has achieved significant technological progress [27].

At present, the most current magnesium reduction technology in the world is the new technology of vacuum smelting of metallic magnesium using internal electrothermal heating. This technology uses electricity as a secondary energy source to heat reaction material from the inside. This technique avoids pollution problems caused by the combustion of materials, increases the reduction temperature, accelerates the reaction process, shortens the reduction cycle, enhances thermal efficiency, and reduces energy consumption. Additionally, it increases the furnace capacity and increases the output of a single furnace. This process does not require expensive metal reduction tanks, and the cost is reduced. Also, it can be designed as continuous production with automatic feeding and automatic discharging, which greatly reduce labor intensity [1].

2.2.5 Heating System of a Reduction Resort

Most magnesium plants in China use coal as fuel. Every 1 t of magnesium produced consumes 8–12 t of high-quality coal. This wastes energy and resources, and also emits a large amount of waste gas, causing serious environmental pollution. From a comparison of the use of clean energy by advanced magnesium smelting enterprises at home and abroad with common magnesium smelting enterprises in China, it is found that the use of clean energy is an effective way to improve magnesium smelting via the Pidgeon process.

The thermal reduction reaction of magnesium smelting can be replaced by microwave heating. Specifically, microwave heating does not use heat conduction to heat but uses high-frequency electromagnetic radiation to act on polar molecules in a material. The violent movement and collision of polar molecules generates heat that can heat materials. In addition to uniform heating, microwave heating is convenient to use to start, control, and stop the heating process, and the temperature can be controlled through adjusting the frequency. Microwave heating can minimize heat loss because the reduction tank can be made of materials that reflect microwaves, thus minimizing microwave absorption. As reported in the literature, "Compared with traditional heating methods, microwave heating has significant advantages such as high efficiency, uniform heating, clean and pollution-free, rapid start and stop heating, easy to control, and improving material properties" [17]. In promoting the application of microwave heating in the thermal reduction of magnesium, the main difficulties are as follows: the conversion efficiency from power to microwaves needs to be improved, and power-microwave conversion equipment with large power still needs to be developed. Although microwave heating has not been applied in the field of magnesium smelting, there have been breakthroughs in the application of microwave heating technology in other metallurgical technologies [18].

2.2.6 Auxiliary Devices

1. Automated equipment used in magnesium smelting

Improvements to the levels of automated monitoring and process control of magnesium smelting can be used to optimize the process flow, enhance the efficiency of magnesium smelting, and decrease entrepreneur's expenses. Moreover, these improvements can effectively reduce the time that workers are exposed to harmful working environments. In addition, the monitoring system that we studied adds units for utilizing waste heat and treating waste gas; thus, effective monitoring of waste heat utilization can be achieved, and it can be ensured that discharged exhaust gas always meets environmental protection requirements.

(1) There are three main approaches for enhancing the mechanization and automation levels of the Pidgeon process. One is the use of a closed joint line that

consists of microcomputer batching, grinding, and pelleting, and the second is the use of mechanized slag removal, tank cleaning, feeding, and magnesium extraction equipment. The closed joint line uses mechanized continuous casting. Advanced foreign enterprises have achieved all three of these points, whereas the current advanced domestic enterprises have only achieved two aspects. Most magnesium plants only achieve one or even none at all, and this indicates that the mechanization level of the enterprises is very low and that improvement is urgently needed.

Siemens WINCC configuration software is used to achieve real-time automatic monitoring of the entire magnesium smelting line. The Siemens S7-1200 or 1500 series PLC is used to carry out temperature and logic controls on the entire magnesium smelting system. When designing the monitoring system, the following aspects are the main concerns:

(1) Utilization of waste heat generated via the calcination process. High-temperature exhaust gas is used to preheat raw materials or to produce hot water. A temperature sensor is used to measure the temperature of the exhaust gas, the temperature of the exhaust gas after waste heat utilization, and the temperature of the raw materials after preheating. The temperature data are sent to the PLC for centralized real-time monitoring. An appropriate sensor should be selected according to the range of the measured temperatures. In principle, the error should be as small as possible, and the price is relatively low. If high-temperature exhaust gas is used to produce hot water, hot water boilers need to be added. Siemens WINCC + PLC can be used to design a set of separated monitoring subsystems for boilers, and these provide more convenient control.
(2) Treatment of exhaust gas. When purifying and removing dust from the exhaust gas after the waste heat is used, it is necessary to determine the temperature of the gas. For gas at a higher temperature, the temperature must be lowered below the maximum temperature that the filter material can withstand. Generally, it should be controlled to be below 120 °C, and cloth bags can be used to remove dust. The cooling methods that are used during bag dust removal include forced air cooling, water cooling, and natural air cooling. The control scheme is determined according to different cooling methods. In this stage, concentration sensors are necessary for monitoring various harmful gases. If the content of emitted harmful gas is within the scope of environmental protection requirements, it is normally discharged. If it exceeds the standard, a warning message is issued to remind the production personnel to take measures to intervene until the requirements are met.
(3) Effective monitoring of furnace temperature, furnace pressure, and flue gas temperature of the reduction furnace. The furnace temperature and temperature of flue gas can be measured using a nickel-chromium and nickel-silicon thermocouple, and the vacuum inside the furnace is measured to determine the furnace pressure. The measured data are input to the PLC host module

through the PLC analog input module. The CPU of the PLC host receives the opening magnitude signal of the combustion valve and the speed control signal of the vacuum pump through PID calculation; the flame size is subsequently adjusted, and the required vacuum degree in the furnace is maintained [22].

2. Automated slagging technology

At present, most of the magnesium plants in Fugo, Shaanxi still use manual slagging. Enduring a long-term harsh environment, which includes dust and high temperature, has seriously harmed the health of workers. There are fewer and fewer people engaged in slagging work although wages continue to increase. Some magnesium plants use forklifts to dig out the slag, and this enhances slagging efficiency and reduces the physical expenditure of workers. However, forklift drivers are still in a dusty and high-temperature environment that is not good for their health. Tan Yuhao et al. [30] invented dust-free automatic slagging equipment for use with magnesium smelting via the Pidgeon process. The machine can automatically remove dust and slag, and this enhances production efficiency. Furthermore, the machine has a slag-collecting device that is convenient for the secondary use of slag. Liang Xiaoping et al. [31] invented a feed device for magnesium smelting that is conducted via the Pidgeon process. The device is equipped with a trolley that moves longitudinally on a horizontally moving trolley. A spiral or air flow slag cleaner is installed on the longitudinally moving trolley, and the longitudinally moving trolley is raised and lowered relative to the horizontally moving trolley. This device has a higher feeding efficiency and effectively reduces the production costs and labor intensity of the workers in the magnesium smelting industry.

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