

Manufacturing Principles of Refractory Magnesia in China

Zongqi Guo, Deli Bi, Shoukuan Sun

Various grades of magnesia are produced by heating natural magnesite in China. In this paper, the detail processes of ordinary sintered magnesia, middle-grade sintered magnesia, high purity sintered magnesia and fused magnesia are summarised. Only ordinary sintered magnesia (dead burnt magnesia – DBM92) is directly produced from natural magnesite. Magnesite is charged in the blend with coal as fuel in a shaft kiln, where calcination and sintering take place in one process. Middle-grade sintered magnesia (DBM95) is made of caustic magnesia that is calcined in a reverberatory furnace, by using a process of calcining, first wet-briquetting strongly, secondary briquetting, drying and sintering. Natural gas has to be used as the fuel in both processes, because high grades of magnesite are downgraded to lower purity of magnesia after sintering. High-purity sintered magnesia (DBM97) is produced by briquetting caustic calcined magnesia and sintered in a shaft kiln fired by cracked oil or natural gas and at the temperature over 1900 °C. After calcining floated magnesite in Multiple Hearth Furnace (MHF), the production of DBM98 is made with the maximum bulk density of 3,37 g/cm³. There is no one of industrial production lines available to produce DBM98 with 3,40 g/cm³ or higher from natural macrocrystalline magnesite, because of the technical limitation in the processes of calcining in reverberatory or MHF and sintering in a shaft kiln. There are four routes to produce fused magnesia in China, namely direct fusion of magnesite, fusion of caustic calcined magnesia, fusion of blends of floated magnesite and caustic magnesia and advanced fusion process with high power, energy saving and clean emission. Magnesite beneficiation provides an opportunity for producing high grades of magnesia. Reverse flotation, removing SiO₂, is a mostly prevailing and effective process to purify magnesite in China at present.

1 Introduction

Global magnesia markets have been dominated by China's production and supply for near three decades [1], thanks to most of natural magnesite deposit (3115 Mt, 26 % of global reserves) and the national open policy in China [2–3]. The largest consumer of magnesia worldwide is the refractory in-

dustry, which consumed about 60 % of the magnesia, the remaining more than 40 % being used in agricultural, chemical, construction, environmental, and other industrial applications [4].

The overview of magnesite deposits in China has been well documented, in terms of metallogenic resource, deposit types and mineralization system [5]. Pure magnesite (MgCO₃) dissociates upon heating to form 47,8 % MgO and to release 52,2 % CO₂, which is noted as the decomposition process. To all natural magnesite, the calcination, sintering and fusion are three types of methods to manufacture magnesia [6]. Calcination is heating up to 1300 °C and brings about thermal decomposition of magnesite, driving off CO₂ from around 600 °C and producing caustic calcined magnesia.

Sintering is the process of densification and crystal growth of periclase by heating at 1500~2000 °C without melting to the point of liquefaction, by reducing porosity in magnesia and increasing the average periclase crystal size in the process of periclase grain boundary motion. Fusion is the process of fusing either calcined magnesia or magnesite ore completely at 2500~3000 °C and crystallizing periclase during cooling. The resultant MgO has different physicochemical properties, which are largely dependent on the origin of the magnesite, the mineralogical composition (periclase crystals and their interstitial phases), and the heating time and temperature. There are gangue minerals existed in natural magnesite, which makes classification of ordinary, medium-grade and high purity magnesia for refractory application. High

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grades of magnesite become less available after long term, continues mining, and therefore, magnesite beneficiation comes up for an indispensable process. Therefore, high efficient utilisations of magnesite demand a better understanding of manufacturing principles of magnesia, particularly in China.

2 Beneficiation of magnesite in China

Magnesite ore is a natural mineral mainly composed of magnesium carbonate, and gangue minerals, such as talc, quartz-based silica, opal, dolomite, and limestone that bring in impurities to magnesia. Modern high-temperature industries lead to considerably increasing demand for high purity magnesium oxide, but high grades of magnesite become difficultly mined in China with years. It has been imperious to develop more efficient methods for magnesite separation from associated gangue minerals to obtain higher grade magnesite. Beneficiation of magnesite is carried out using physical, chemical and physicochemical methods, but only a few of processes are interested to upgrade magnesite quality for refractory manufacturing [7].

The talc-rich magnesite rocks have to be firstly sorted out by miners during truck loading. The chemical process is used to purify magnesite in which impurities are micro-disseminated. Magnesite is calcined firstly to improve its surface activity and to increase its solubility, and then leached with reagents such as hydrochloric acid, nitric acid, sulphuric acid and ammonium salt, precipitating and separating the impurities to obtain high-purity MgO products.

There is no special requirement on grade and size of magnesite, but this process takes long duration and huge energy consumption, with large initial investment. Gravity concentration is a separation method by the density differences of magnesite and gangue minerals. Owing to small difference of their specific gravities, the direct utilisation of gravity concentration has poor efficiencies. The heavy medium separator is suitable for dealing with the lower grade of magnesite bulk ore (>3 mm), with high magnesite recovery to replace artificial sorting.

Flotation is the most effective and extensively used method to separate magnesite ore and gangue minerals in accordance

with the differences of physicochemical properties of their surfaces [8, 9]. It is generally used for the separation of fine magnesite ore, which can obtain high-grade concentrate. Main impurities in magnesite ore can be divided into silicates (mainly including talc, quartz, etc.) and the carbonate (dolomite, calcite, etc.). The flotation separations of magnesite are made with alternation of reverse and direct flotation, firstly using lauryl amine collector to make reverse flotation of siliceous minerals and then using fatty acid collector to have direct flotation of magnesite [10].

In the second step, sodium silicate and sodium hexametaphosphate can be added to selectively inhibit dolomite and calcite minerals. For magnesite ore and gangue minerals of dolomite, talc, tremolite, quartz, etc., with 91,19 % MgO and 3,19 % SiO₂, the combination of reverse/direct flotation processes have upgraded the concentrate of 97,71 % MgO and 0,28 % SiO₂, with the yield rate of 71,82 %, under the suitable conditions of grinding fineness and reagent degree [11].

For magnesite ore with talc and quartz as the main gangue minerals, high grade of magnesite can be achieved only after reverse flotation using amine cationic as collector [12]. When the pH of the medium is greater than zero of quartz isoelectric point (pH = 2~3,7), the surface of quartz absorbs OH⁻ ions in the medium, and the outer attracts H⁺ ions. This is the formation of electric double layer. The amine cationic exchange adsorption of H⁺ in outer layer, leading to quartz hydrophobic. At this moment, lauryl amine well floats quartz. The isoelectric point of magnesite is at pH = 5,5. If the pH > 5,5, the surface of magnesite absorbs negative charge and lauryl amine can float magnesite. When the pH > 7, the electro-negativity of quartz is stronger than that of magnesite, so the preferential adsorption of cationic make the two minerals be effective separation. Flotation process for magnesia purification has advantages of variable flotation reagents, low cost, economic feasibility.

Therefore, many flotation lines in China are in running and under investment to upgrade high silica containing magnesite. The silica travels into the magnesite from different sources and its existence within magnesite is in the following forms [13]:

- Body silica: it exists within the crystal system and its size is about 8~10 μm. Its content within the magnesite is about 0,20 % and it is really impossible, at least by flotation, to remove this silica from the body;
- Primary originated silica minerals: They usually occur in the form of crack fillings during the genesis of magnesite and their grain size depends directly upon the size of these cracks;
- Secondary originated silica minerals: These are the minerals like talc and serpentine. Regarding to the current industrial situation, the flotation is focusing on removing silica from natural magnesite, i.e., 95~96 % MgO grade of magnesite is floated to upgrade to over 98 % MgO by removing 2~3 % SiO₂ in most of magnesite flotation lines in China [14].

3 Caustic calcined magnesia

Caustic Calcined Magnesia (CCM) has been directly used in industrial, agricultural and other applications in great quantity, in addition to the production of dead burnt magnesia and fused magnesia [4]. Because 52,2 % CO₂ has to be driven off during calcination, it is difficult to make compromise of capacity, activity, eco-friendly and cost of CCM in industrial practice. The optimal calcining temperatures are different, depending on the type of calcining furnace. Too high temperature leads to the reduction of the activity of caustic magnesia. On the contrary, the decomposition of magnesite is not well completed at the insufficient temperature, and then the loss on ignition is over 3 %. There are three types of furnaces to produce caustic calcined magnesia in China.

3.1 Reverberatory furnace

As illustrated in Fig. 1, the simplest reverberatory is nothing more than a hearth lined with refractory bricks, connecting a firebox at one side. About 3~4 t of a block magnesite ore is fed into the hearth from the top every two hours, and the hot gas is provided from the firebox beside. 1,5~2,0 t of caustic calcined magnesia is discharged at the bottom every 2 h. Magnesite is calcined in reverberatory furnaces, with the following circumstances:

- Due to large amount of CO₂ emission, only 50~300 mm lumps are accepted for

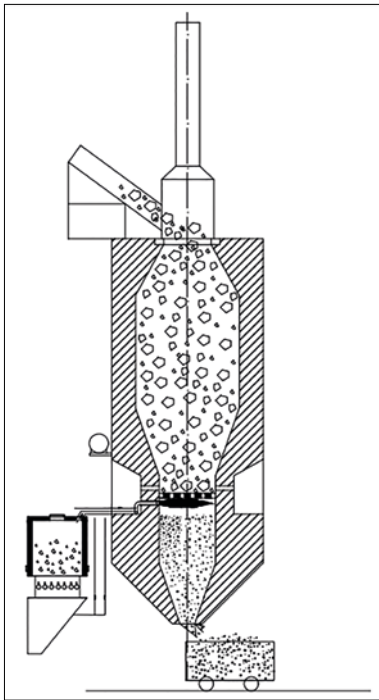


Fig. 1 Schematic diagram of reverberatory furnace

calcination because smaller lumps and fines would block gas flow in the hearth, with a risk of explosion. Small and fine magnesite ore is abandoned by reverberatory furnace.

- In order to make the loss on ignition of less than 3 %, the calcining temperatures are controlled between 1100–1300 °C, which have reduced the activity of some CCM.
- A reverberatory is operated intermittently with limited daily output. Usually, 15–20 reverberatories are built on one line for a designed capacity.
- Many reverberatories are fired by the combustion of coal. There are problems of incomplete combustion, dusting and high emission.

3.2 Multiple Hearth Furnace (MHF)

In the calcination of magnesite powder, particularly floated magnesite with some moisture, MHF is preferred for years, where 18–19 hearths are built with the inner diameter of 7 m and the height of 1 m for each hearth, as shown in Fig. 2. The floated magnesite paste is fed to the top of the furnace and slowly moves with the role of scrapers in each hearth until lightly calcined magnesite is discharged from the bottom.

The upper hearths are to remove free water, the middle hearths remove combined moisture and volatiles, and the lower hearths calcine magnesite.

To obtain high activity of CCM, a carefully controlled temperature profile is required. The temperature profile ranges from 400 °C at the top to 1000 °C at the bottom of MHF, fired by natural gas. The exhaust gases carry with some of magnesite (~20 %) as dust which is drawn from MHF and cleaned in a bag filter unit which strips out magnesite and allows the clean gases to pass to atmosphere, the collected dust being returned to the middle section of MHF. The material moves inside MHF for around 3 h, with a possibly changeable output of 150–300 t/d.

3.3 Suspension calciner

The latest development is to calcine magnesite in a suspension calciner, which is a high vertical cylinder with 1,8 m in inner diameter and 30 m in height, and where magnesite powder rapidly moves from the bottom to the top in 3 s, travelling with hot gases from combustor. Fig. 3 is an illustrated diagram of the suspension calciner.

Magnesite powder decomposes during fast movement and therefore the calcining temperature could be close to theoretical decomposing point, which is much lower than that in reverberatory furnace and MHF. The activity of CCM should be high, without any over-calcined magnesite. It is believed that CCM made by suspension calciner has significantly high activity, with large capacity and eco-friendly operation. The output of suspension calciner is 300 t/d CCM with the ensured compacity for an industrial manufacturing line.

The operating parameters of reverberatory, MHF and suspension calciners are collected from three production lines, which are summarized in Tab. 1. The advantages of suspension calciner are obvious, in terms of flash decomposition, compacity and activity of ground CCM.

4 Dead burnt magnesite

Dead Burnt Magnesite (DBM) includes ordinary magnesite (DBM92), middle-grade magnesite (DBM95), high-purity magnesite (DBM97) and super high-purity magnesite (DBM98). Their sintering processes are summarised in Tab. 2. All grades of DBM are

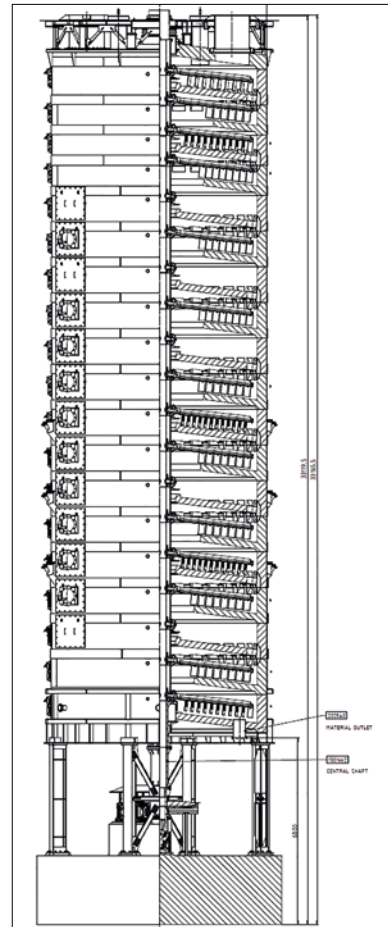


Fig. 2 Multiple hearth furnace for calcining magnesite

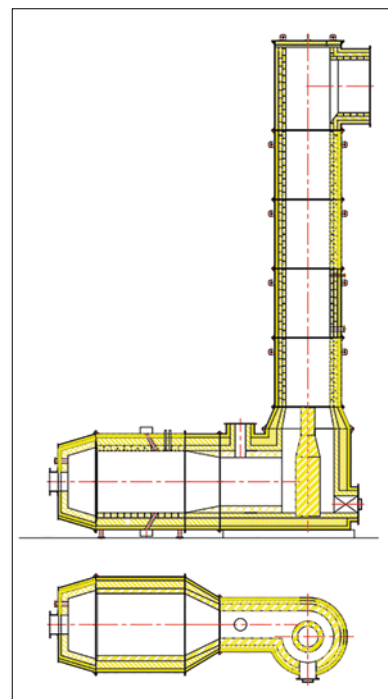


Fig. 3 Suspension calciner to calcine magnesite

Tab. 1 Comparison of reverberatory, MHF and suspension calciner to calcine magnesite

Type of Calciner	Reverberatory Furnace	Multiple Hearth Furnace	Suspension Calciner
Feeding magnesite ore	50~300 mm block	<0,074 mm	<0,074 mm
Calcining temperature [°C]	1100~1300	850~1100	650~850
Calcining duration	3 h	3 h	3 s
Operation mode	Intermittent	Continuous	Continuous
Calcining status	Static stacking	Mechanical driving	Fast flowing
CCM output rate [t/d]	20~30	150~300	300
CCM ground size D ₅₀ [µm]	45	10	5
CCM activity*, second	180~200	60~80	30~40

*reaction time is determined by using the citric acid method

sintered in a shaft kiln in China. DBM92 is the lowest grade of sintered magnesia for the manufacture of basic bricks, with the acceptable scrap rate of burning deformation in tunnel kiln. It is sintered directly from raw magnesite lumps solely. The contemporary shaft kiln is unsuitable to process magnesite with a grain size below 50 mm. The higher grades of sintered magnesia are achieved in two-step process of calcination and sintering.

After magnesite decomposes into MgO and CO₂, Mg²⁺ and O²⁻ remain in the original position as CO₂ is released. MgO still keeps the outside skeleton of the original crystal [15]. It is shown that calcined MgO fine grains consist of aggregates with pseudomorph of magnesite and large gaps exist between the aggregates. By fine grinding

calcined magnesia, the pseudomorph of aggregates is disrupted to a great extent, so the specific surface area is increased and their activity becomes higher.

This is the major reason why most of natural magnesite, particularly macrocrystalline, cannot be directly burnt to dense magnesia for refractory manufacture.

The caustic calcined magnesia has to be ground and briquetted, which is a critical step for the densification of sintered magnesia.

A series of variables, such as the fineness of caustic magnesia, dry or semi-dry process and specific pressure, etc., have a great effect on the density of briquettes and then sintered magnesia [16]. The preferred briquettes of olive shapes can be manufactured by dry process with the size of

38 mm × 26 mm × 16 mm. The briquettes larger than 16 mm are transported for drying and curing, and those smaller than 16 mm are returned to the briquetting system.

Raw ore or CCM briquettes are charged in the top of the shaft kiln, which is a vertical working apparatus [17, 18]. They move downwards in the sequences through the zones of preheating, sintering and cooling, and finally collected by the discharging unit and the electric vibrating conveyor. The production of sintered magnesia is a high-temperature process with high demands on energy consumption. One common issue is to ensure uniformity of the sintering process through the kiln cross section. Some critical parameters have to be reviewed for production operation of high temperature shaft kiln [19, 20].

- The high temperature (1900 °C) obtained in the shaft kiln can be achieved by supplying sufficient heat, which is guaranteed by less than 0,066 m² of cross section of the kiln, covered by each burner.
- The size of briquettes is one of the decisive factors for the shaft kiln to achieve a high output. The utilisation index 7 t/m³ of the kiln is easily to be approached during the normal operating condition. Under identical condition, the time needed for sintering and cooling of briquettes is directly proportional to the square of average briquette diameter.

Tab. 2 Sintering process of various-grades DBMs

Magnesia Grade	DBM92	DBM95	DBM97	DBM98
Terminology	Ordinary Magnesia	Middle-Grade Magnesia	High-Purity Magnesia	Super High-Purity Magnesia
Grade of magnesite ore (L.o.I.-free magnesite)	95,5~96,5 % MgO	96,5~97,5 % MgO	96,5~97,5 % MgO	95,5~96,5 % MgO
Magnesite ore size [mm]	50~300	50~300	50~300	<0,074
Floatation	Non	Non	Non	Removing 2~3 % SiO ₂
Calcination	Non	Reverberatory	Reverberatory	MHF
CCM grinding D ₅₀ [µm]	Non	45	45	10
CCM briquetting	Non	Wet, double	Dry, double	Dry, double
Drying/curing briquette	Non	5~7 days	5~7 days	5~7 days
Sintering facility	Shaft kiln Ø 2,5 m × 16,5 m	Shaft kiln Ø 1,8 m × 15 m	Shaft kiln Ø 1,7 m × 11 m	Shaft kiln Ø 1,6 m × 11 m
Fuel of shaft kiln	Mixed with coal	Mixed with coal	Natural gas/LPG	Natural gas/LPG
Sintering temperature [°C]	1550~1750	1750~1850	>1900	>1900
Output of shaft kiln	Lump	Ø 40/60 mm	Ø 30 mm	Ø 20 mm
MgO content of DBM [mass-%]	92~94	94~96	96~98	>98
Bulk density of DBM [g/cm ³]	3,10~3,25	3,20~3,25	3,25~3,30	3,35~3,37

- The calcination of magnesite plays an important role in raising the production efficiency of the shaft kilns owing to the fact that decomposition of magnesite is basically completed during calcining. The CCM with the most activity determines the densification degree of sintered magnesia, significantly.

Cracked oil or natural gas are used as fuel and compressed air functions as primary air. The cooling air supplied by the air blower goes through the upper periphery of the discharging unit and then enters into the kiln [21]. The air moves in counterflow with respect to the magnesia in the kiln. The cooling air functions as secondary air necessary for combustion continues to go upwards, an intensive heat exchange takes place between the air and the high temperature briquettes.

Before entering the sintering zone, briquettes are preheated to over 1500 °C. The secondary air is mixed with atomized fuel and fired in front of the burners in the sintering zone. The firing temperature is higher than 1900 °C. The flue gas generated is cooled down about 500 °C after passing through the preheating zone, and then goes further via a gas pipe to the dust collector for dedusting. The sintered magnesia discharged from the kiln is cooled down to 50–60 °C. The shaft kiln is operated under positive pressure, except for slightly negative pressure kept at its top.

In the sintering of DBM92 and DBM95, coal and coke as fuel are blended with raw magnesite ore or CCM briquettes. For sintering DBM97 and DBM98, in the lower part of the kiln is located the combustion burners of natural gas and air. DBM97 contains small amounts of impurities, such as SiO₂, CaO, Fe₂O₃ and Al₂O₃, etc. and so it is hard to get sintered with high bulk density, which is 3,24–3,28 g/cm³ for most commercial products, up to 3,30 g/cm³ in best production.

Cracked oil, earlier used, and natural gas, commonly now, are used as fuel, with their high heat value and without residual contaminations. DBM98 is only made of the floated magnesite in China and the bulk density of DBM98 is within the range of 3,35–3,37 g/cm³.

There are two industrial lines invested and operated, including reverse flotation line to remove some SiO₂ in magnesite ore, cal-

ination in a MHF and sintering in a RCE shaft kiln. They are well run, respectively with the capacity of 50 000 t/a DBM98 and 50 000 t/a fused magnesia FM98. However, raw ore is in the risk of shortage, from time to time, because of the limited availability of magnesite with high SiO₂ content, and the bulk density of sintered magnesia never is on the expected level [22].

If the relative density of magnesia reaches 95 %, the bulk density is 3,40 g/cm³, being the minimum expectation of sintered magnesia. On the basis of the industrial practice in several decades and the endeavour of huge investments, it is believed that it is impossible for sintered magnesia to reach 3,40 g/cm³ in the bulk density from natural macrocrystalline magnesite, by the processes of calcining in reverberatory or MHF and sintering in a shaft kiln, due to the technical limitation.

The studies [23, 24] were to hydrate CCM and to recalcine magnesium hydroxide, finally to sinter at the temperatures of 1600–1700 °C. In the three-step sintering process, it was easy for DBM98 to achieve the desired bulk density that is over 3,45 g/cm³. In spite of additional investment of recalcining magnesium hydroxide, this process would be feasible in industry to replace ultra-high temperature sintering if the cost of fuel becomes very high.

5 Electric fused magnesia

5.1 Fusion equipment and process

The arc melting method is used to produce Fused Magnesia (FM), by generating high temperature of over 2800 °C. Magnesite ore experiences heating-up, CO₂ dissociating, fusing, crystallizing, crystal growing and cooling. An important step is to convert electric energy into heat energy and light burned magnesia or raw magnesite are melted at the high temperature to form a molten pool.

Electrical arc furnace consists of vertical three-phase electrodes located at the tips of triangles in a cylinder container. The production equipment mainly includes: feed bin, hoisting machines, feeding machine, furnace body, graphite electrode, electrode clamping arm, electric furnace transformer, plant substation, dust collector, cooling system, and crusher. Hoisting machine lifts raw

material to feed bin. It is fed slowly to the mouth of furnace in the pipe by the feeding machine. The outer surface of the cylinder furnace is sprayed by cooling water from the circular pipe to extend the life of furnace shell.

The overheated and the underheated portions have to be minimised in the furnace. In the smelting process, the electrodes are continuously ablated. When the electrode is not long enough, new electrode section is connected by using the electrode buckle. The electrodes have good electrical contact with the copper tile by the electrode clip of clamping arm with the copper tile and cone ring gripper. The cooling water flows inside the hollow interior of the copper tile and the gripper. An overview has been done to cover the manufacturing equipment and process of fused magnesia [25].

There are three major phases in fusion process, as follows [26].

- Start-up stage: raw magnesite ore in the sizes of 30–50 mm is fed into the bottom of fused magnesia furnace, as bedding course in 400 mm high. The three electrodes are lowered to localise their sites. Small lumps of graphite scraps are used to connect three sites with electrodes. After arc is generated, 800 mm thick magnesite lumps are loaded to the furnace. The melting initializes with the voltage of 120 V, and continues for 2 h, in order to generate the melting pool. MgO and CO₂ generate simultaneously during fusing, and CO₂ forms bulbs under the electrode. It takes more energy to drive off small size of the bulb. Too large size of the bulb could cause unstable current, vigorous splashing, and subsidence area, followed by arc suppressing and short circuit. When the current is unsteady, the electrodes have to be raised to 200–300 mm by manual operation, one by one and 2–3 times. In order to release the bulbs, magnesite lumps are loaded around the electrodes and magnesite fines are put near the furnace shell. Obviously, a great quantity of exhaust gas and dust are generated.
- Steady melting stage: when the melting pool forms, the current is 150–160 V. It is stable melting process. As the electrodes move up, the bulbs release automatically. Steady melting phase should last at least 6 h. The problem could be small output of

fused magnesia because fast moving-up of the electrodes. As solutions, manually releasing of bulbs and lowering of electrodes can increase the current, and then the output.

- Finishing stage: The voltage remains at 120~130 V for about 2 h before shutting down of fused magnesia furnace. In the finishing phase, it is important to have manual feeding of caustic calcining magnesia fines to reduce bulb releasing, and porosity existing in fused magnesia. The melt lump needs natural cooling period. The molten MgO is crystallized by cooling, which takes about one week.

5.2 Production route

There are four routes to produce fused magnesia in China, which have summarised for comparative life cycle assessment of conventional and new fused magnesia production [27].

One step route: natural magnesite as raw material is molten directly in melting furnace, with the largest industrial scale. The periclase crystal size is 400~500 μm in average. Two step route: natural magnesite is calcined in a reverberatory furnace to have caustic calcining magnesia. The briquettes of CCM are fed and molten in melting furnace to produce fused magnesia. By using the two step route, it is easier to form large periclase crystals in fused magnesia, being 800~1000 μm in average.

The hybrid route: the concentrated magnesite is produced by floating the fine grinded powder of low grade magnesite in flotation cells and then concentrating the floated ore pulp in a thickening pool. The blends of concentrated magnesite and 20~30 % CCM as binder are briquetted and molten to manufacture fused magnesia. The advantages lie in using low grade of magnesite and producing higher grades of fused magnesia than that of one-step output.

The sustainable route: the overall process [28–29] is upgraded in order to reduce energy consumption and CO₂ emission. There are the following characteristics:

- Crushed magnesite ore is preheated through a preheating chain grate by the flue gas generated from the electric arc furnace and the hot air from the cooling chain grate. The hot charging and hot delivery make heat recovery from flue gas.

- The cover of the furnace is used. From the fourth hole on the cover, the hot flue gas of the smelting process is collected centrally to the preheating grate, which can help recycling fine ore with the flue gas as well. It is critical for both the energy saving and environmental protection of the FM production.
- Newly fused magnesia column is enforced for heat convection with air in a heat exchange chamber until the completion of periclase crystallization. Then the fused ingot is broken into blocks and cooled in the cooling grate. The heat can be recycled for cascade utilisation of preheating the raw material.
- The flue gas generated in FM production is cooled by passing the preheating grate. After dust removal and recovery of CO₂, the collected CO₂ can be used for the resource of chemical products. In summary, the preheating of raw material, the covered furnace, the thermal insulation of the furnace body, and the rapid cooling in the process of periclase crystallization can improve the grade of FM product.

5.3 Key fusion process parameters

Many fused magnesia producers prefer small electric arc furnaces in China, with the power capacity of the transformer in the range of 600~2000 kVA. The conventional technologies lead to high energy consumption,

severe pollution, high labour intensity [30]. The energy consumption is up to 3000 kWh/t for fused magnesia, which is significantly higher than the international average 2800 kWh/t of advanced technology.

The upgraded technology includes 3000 kVA constant power transformer, steel cover cooled by water and a centralised dedust system [31]. The electrode holes and material feeding door are sealed to prevent smoke and dust leakage. Main parameter comparison between upgraded and conventional melting equipment is listed in Tab. 3.

In the study of Qi, et al [32], effects of electrode diameter and depth buried in melting magnesia are investigated on the arc heat ratio, which increases with rising electrode diameter at first, reaches the maximum at about 400 mm and decreases with larger diameter. The optimal range is 350~450 mm of electrode diameter for 3000 kVA melting furnace. The immersion depth of electrodes is determined as 300 mm into the molten pool.

Three fusions are made in 3000 kVA facility, as shown in Tab. 4. The melting voltage is 145 V and the melting current 12,5 kA. After 10 h melting, coarse raw material in Case 2 results in 518 kWh/t energy saving compared to more fine grains in Case 1. When the recycled outer layer of fused magnesia is used with coarse magnesite ore, the power consumption is the lowest

Tab. 3 Comparison of main parameters for melting equipment

Parameter		Conventional Furnace	Upgraded Furnace
Power of transformer	kVA	1600	3000
Second voltage range	V	90~150	100~180
Current limit of electrode	kA	7,5	21
Rated frequency	Hz	50	50
Diameter of electrode	mm	250	300~400

Tab. 4 Power consumption of different sized raw materials

Raw Material and Parameter		Case 1	Case 2	Case 3
Ratio of raw magnesite [%]	50~80 mm	35	40	30
	20~50 mm	32	55	45
	<20 mm	33	5	5
	Outer layer of fused magnesia column			20
Total power	kWh	22 640	24 480	24 120
Fused magnesia	kg	6757	8644	9422
Consumption	kWh/t	3350	2832	2560

for each tonnage of fused magnesia. The big problem is the horizontal section of fused magnesia looks like quincunx shape in Case 1, instead of round section. Under high temperature of the electric arc, three melting pools form under the electrodes. The MgO mass transfer process is hindered in Case 1 that much finer magnesite powder presented in raw materials, which leads to the quincunx formation. Quincunx boundaries have to be avoided because the qualified MgO productivity becomes much lower.

In Case 2 with much less fine magnesite, there is no quincunx boundary observed. The diameter of the melt section is 1400 mm, much larger than that (950 mm) in Case 1. It is important to screen the fine magnesite from raw materials. Since the decomposition process has finished in the outer layer of fused magnesia in Case 3, its addition further improves energy saving and productivity, with larger melted section of 1650 mm.

The latest developments of FM facilities include 5000–8000 kVA, 180–230 V, 10.5–13.5 kA and 400–500 mm in the diameter of electrodes, for fusion process directly from raw magnesite, as well as 4,000–5,000 kVA, 105–135 V, 20 kA and 300–400 mm of the electrodes' diameter for fused magnesia from CCM briquettes.

Li made life cycle assessment of fused magnesia production [33]. Environmental impacts caused by indirect high power consumption and CO₂ emissions are two major factors of traditional FM process. The newly developed FM process presents the best performance across all the environmental categories and through the entire life cycle. It was pointed that the environmental benefits will be significant, and considerable revenues can also be had from saving energy and producing CO₂ by-products at the same time, although the one-time investment needed to upgrading to new process may be high.

6 Summaries

Only ordinary sintered magnesia (DBM92) is produced directly from natural magnesite in China. Magnesite is charged in the blend with coal as fuel in a shaft kiln, where calcination and sintering take place in one process. The latest developed kilns allow

continues loading/unloading and closed sintering system, with clean emission and high consistent bulk density. Middle-grade sintered magnesia (DBM95) is made of caustic magnesia that is calcined in a reverberatory furnace, by using a process of calcining, first wet-briquetting strongly, secondary briquetting, drying and sintering. The problem of both production processes is that high grades of magnesite are used to produce lower purity of magnesia.

High-purity sintered magnesia (DBM97) is produced by briquetting high grade of caustic calcined magnesia and sintered in a shaft kiln fired by cracked oil or natural gas and at the temperature over 1900 °C. After calcining floated magnesite in MHF, production of DBM98 is made with maximum bulk density of 3.35–3.37 g/cm³. The industrial practices reveal that it is impossible for sintered high-purity magnesia to reach 3.40 g/cm³ or higher of the bulk density, from natural macrocrystalline magnesite by calcining in reverberatory or MHF and sintering in a shaft kiln.

There are four routes to produce fused magnesia in China, namely direct fusion of magnesite, fusion of caustic calcined magnesia, fusion of the blends of floated magnesite and caustic magnesia, and advanced fusion process with high power, energy saving and clean emission.

Magnesite beneficiations provide a manufacturing opportunity of high-grade magnesia. Reverse flotation, removing SiO₂, is the commonest process to purify magnesite in China at present.

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