TECHNICAL OPTIMIZATION OF SHAFT FURNACES FOR THE SINTERED MAGNESIA PRODUCTION

Imrich Kostial[1)*], *Dusan Nascak*[1)]
[1)] *Technical University of Košice, Faculty of Mining, Ecology, Process Control and Geotechnology, Košice, Slovakia*

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[*]Corresponding author: *imrich.kostial@tuke.sk, tel.: +421 55 602 5177, Development and realisation workplace of raw materials extracting and treatment, Faculty of Mining, Ecology, Process Control and Geotechnology, Technical University of Košice, Letná 9, 042 00 Košice, Slovakia*

Abstract
The contemporary shaft furnaces for the production of sintered magnesia have a very good performance. However, there are still significant possibilities of their improvement. Thermodynamic, hydrodynamic and rheological processes don't run optimally. The purpose of the research was to determine the reasons and realization of optimization measures. One of the significant requirements was to process materials with lower granularity (20 - 40 mm). The improvement was focused on the charging system modification, burner system modification, coke utilization in the central part of the furnace, sinter heat utilization, increasing the insulation. Their verification was reached at the operational conditions. The result was conceptually new pilot shaft furnace, determined for the further research. The basic features of the new shaft furnace are distributed burners improving combustion of the secondary air flowing through the central part of the furnace. By this approach significant improvement of the temperature homogeneity through the furnace cross section is achieved.

Keywords: sintering, thermomechanical processing, thermodynamics, shaft furnace, magnesia processing, technical optimization

1 Introduction

Slovakia has 1.9 % of the magnesite global reserves and provides about 5.8 % of the world production of dead-burnt magnesia [1]. Production of the sintered magnesia from natural magnesite of amount 8.5 million tones is concentrated in 12 countries. Production of the sintered magnesia is a high-temperature process with high demands on energy consumption. The basic disadvantage of the contemporary shaft furnaces is their unsuitability to process magnesite concentrates with a grain size below 40 mm [2]. One of the biggest problems is to ensure uniformity of the sintering process through the furnace cross section. The processes, products and technologies optimization achieving the potential use created by the innovation measures, presents the second fundamental aspect of the success. The present work deals with the technological modifications consideration of the existing shaft furnaces for sintered magnesia production.

Shaft furnaces are basic thermal apparatuses widely used for the granular materials thermal treatment. They are used for the ores and concentrates treatment, iron production, ceramic and

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refractory materials, fuel gasification, in chemical industry and etc. Very important is their application in the carbonate industry for calcination and sintering [3, 4]. The shaft furnace is a vertical working apparatus. The batch with a fuel and other ingredients needed as a source of thermal energy or as a chemical substance is charged into the top of the furnace. The motion of the material is downward motion and chemical reactions run during the material motion through the shaft. The material is collected in base of the furnace. In the lower part of the furnace is located the combustion air inlet or mixture of gas and air inlet ensuring a heat generation and necessary technological processes [5]. Horizontal cross section of the furnace shaft ensures the uniform distribution through cross section of the furnace. Width of the furnace of oval or rectangular cross-section of the shaft is mostly about 1 to 2.5 meters [6, 7]. The furnace with an output of 2.5 t/h for magnesite calcination is shown in **Fig. 1**. Processing of the magnesite in the shaft furnace consists of following operations: a) drying, b) calcination (decarbonisation), c) sintering, d) cooling [8, 9, 10].

2 Experimental material(s) and methods

Necessary condition for shaft furnace operation is breathable fixed granular batch. A typical representative of such devices is the shaft furnace. Shaft furnace experiments were executed on the operating furnace and by simulation on the developed mathematical model [11].

2.1 Modelling of the shaft furnaces

For the modelling purposes, the shaft furnace is divided into zones (**Fig. 2**) with the same type of flow of the gaseous medium: a) counter current flow - the zone 1 and 3; b) a combination of cross and counter current flow - zone 2 [12,13,14,23].

Fig. 1 Shaft furnace for magnesite sintering-general view

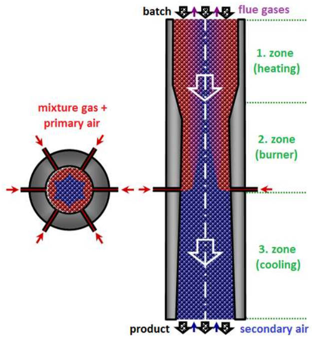

Fig. 2 Hydromechanical shaft furnace profile

The mathematical model was designed as a stationary two-dimensional model. The material flow is considered as piston due to modelling needs and considering width. It cases an uneven flow of the gaseous media through the device. For the modelling needs, flow has horizontal section, simplified transformed shape.

The basic types of the flow of the gaseous medium includes: a) a counter current flow of gas flowing in a direction opposite of the material; motion of material is from top to bottom and motion of gas is to the contrary (**Fig. 3a**); b) bypass (**Fig. 3b**) - gas flows around the part of the material layers; c) combinations (one side input of medium (**Fig. 3c**), more side inputs of media (**Fig. 3d**), a movement of side input of the medium into the furnace (**Fig. 3e**).

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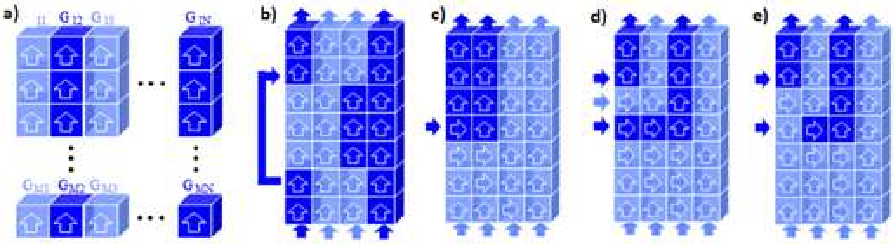

Fig. 3 Shaft furnace flow models
a) counter current flow, b) flow with bypass c) flow with one side input, d) flow with three side inputs, e) flow with shifted side input

The model consists of two primary mixing and the mixing of the vertical and horizontal and combinations thereof (**Fig. 4** - G is the mass transfer). Active surface is the exchange surface between the material and the gaseous medium (**Fig. 5**) [15, 22].

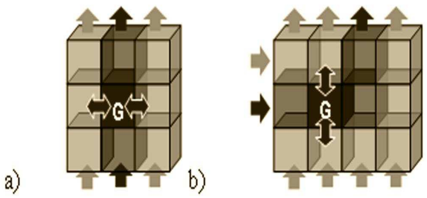

Fig. 4 Mixing of gaseous media a) vertical, b) horizontal

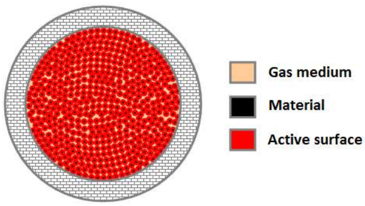

Fig. 5 Shaft furnace cross-section

Mass and heat balance can be compiled for the entire furnace or separately for some parts of the furnace. For the processes carried out in the shaft furnace, the mass and heat balance is maintained [16, 17, 18, 20].
The equation to calculate the material heat:

$$Q_{mat} = m_{mat}.c_{p\_mat}.t_{mat}.1000 \quad (1.)$$

where: m_{mat} [kg] - material weight, c_{p_mat} [$kJ.kg^{-1}.K^{-1}$] - specific heat capacity of the material, T_{mat} [°C] - the material temperature.
Heat consisting of gaseous medium:

$$Q_{med} = V_{med}.c_{p\_med}.t_{med}.1000 \quad (2.)$$

where: V_{med} [m^3] - volume of gaseous medium, c_{p_med} [$kJ.m^{-3}.K^{-1}$] - specific heat capacity of gas, T_{med} [°C] - temperature of the gaseous medium.

2.2 Shaft furnace present state

Raw material qualitatively suitable for use in the existing shaft furnaces taking into account its chemical composition and grain size composition is slightly below 30 %. Further increase in the total production of the magnesite sinter in the shaft furnace is conditioned by optimizing the current furnace or development of a new type of the shaft furnace.

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Proposal of technologically optimal furnace is mainly focused on the flow conditions changing, combustion and decrease in heat losses (**Fig. 6**). The production process optimization of magnesite processing in the shaft furnace is based on a comprehensive analysis of individual production processes or their features and links [19].

2.3 Technical optimization

The aim of technical optimization including changing design parameters of the device is to find the optimal operating conditions corresponding to minimum special-purpose functions. For evaluating the effects of the optimization steps, a range of criteria and energy, environmental and economic indicators can be developed.

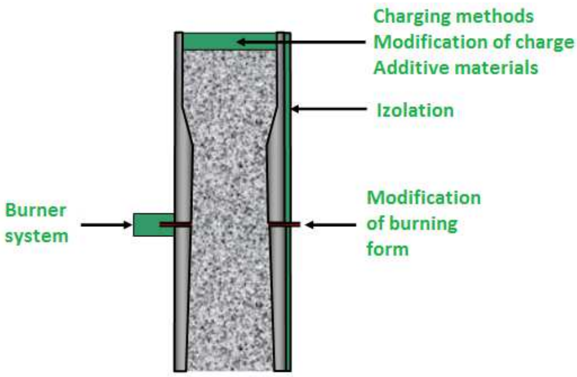

Fig. 6 Shaft furnace optimization options

2.4 BAT technology

BAT analysis (best available technology) is regarding an evaluation of the current system. BAT is related to the current utilization of the shaft furnace No. 14 which is considered as a reference furnace for further aims. Simulation of alternative furnaces with input and output parameters is shown in **Table 1** and **Table 2**. The basic indicators of the BAT evaluation are following: a) economic - cost, etc.; b) technical - durability, safety; c) technological - quality, performance; d) environmental - air pollution, flue dust; e) process – courses of the critical process quantities. Selected BAT indicators of the reference furnace are shown in **Table 3**.

Table 1 References shaft furnace inputs

Charging material

Mass flow		4 750	kg/h
Temperature		20	°C
Composition	H_2O	0.5	%
	$FeCO_3$	5.03	%
	SiO_2	0.84	%
	$CaCO_3$	5.62	%
	$MgCO_3$	87.85	%
	Al_2O_3	0.15	%
ρ_{mat}		3 000	kg/m^3
Average grain size		70	mm

Input media

Natural gas	360	m^3/h
Primary air	3 700	m^3/h
Secondary air	1 500	m^3/h

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3 Results

Technologically optimally working furnace specifies technological optimum or limits of the furnace working. The difference between the furnace options and the reference state is conveyed by the optimization potential of the shaft furnace. These limits are not absolute.

Based on analysis the following optimization of the existing technologies were developed: a) changing the charging method - shorter cycles of the charging and new top furnace, b) calcined anthracite charging, c) the use of water for the secondary air cooling.

Table 2 References shaft furnace outputs

Product

Mass flow		2 150	kg/h
Temperature		704.6	°C
Composition	FeO	6.49	%
	SiO_2	1.59	%
	CaO	6.89	%
	MgO	84.74	%
	Al_2O_3	0.28	%

Flue gases

Flow rate		6 995	m^3/h
Temperature		212.5	°C
Composition	N_2	59.03	%
	O_2	5.94	%
	CO_2	24.99	%
	H_2O	9.68	%
	CO	0.25	%
Waste gas		322.5	kg/h

Table 3 BAT indicators for the reference furnace No. 14

	Reference state
consumption of natural gas	170 Nm^3/t
consumption of electric energy	55.7 kWh/t
furnace performance	2.15 t/hod.
volume of waste gas	0.15 t/t
CO in flue gases	6000 ppm
NO_x	18 mg/m^3
bulk density	3.30 g/cm^3
uniformity of firing	±0.10 g/cm^3
operational reliability of solution	9 months

3.1 Charging method modification

The problem about present shaft furnace charging has been related to the fact, that while a standard technology process with fuel supply, primary air, secondary air and normal dust discharge from the furnace has been carried out during one charging cycle of 55 min/h, a significant reduction in the dust discharge from the value 4 – 4.2 kPa to the value of 1.8 – 2.2 kPa has been occurred during feeding the material into the furnace for about 5 min. per 1 hour. There has therefore been an increase in pressure in the sintering zone. In addition, passing the flue gas at the middle of the furnace has been getting worse and temperature difference between the burners´ holes and the centre of the furnace has been increased. Thus, differences related to the temperature profile of the furnace and differences of T_{max} a T_{min} in the burner zone have been increased. An insufficient flue gases discharge from the furnace area has resulted in worse level of the blending natural gas and primary air. There is the possibility to provide a half an hour cycle of the input raw material feeding due to better preheating. Design of

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the new furnace top consists of establishing charging system with two shutters (upper and lower) and hopper, which will prevent the raw material from an aspiration of “false” air during the feeding (**Fig. 7**). Double shutter of the top furnace is used to prevent false air intake through the hopper and thus achieve effective temperatures and concentrations in the relevant zones of the shaft furnace. Difference between electricity consumption at the period of the normal operating mode and at the material feeding with draft fans is 7.4 kW, at the primary blower – 2.3 kW, at the secondary blower – 2.5 kW. Since the furnace works 5 min/h at this mode, then the total energy saving is 1.02 kW/h. In financial terms, it is about € 8.400 annually. Comparing the expected impact with reference state, these changes has been emerged: 1) consumption of electric energy: - 0.9 %; 2) CO in flue gases: slight improvement; 3) bulk density: slight improvement; 4) uniformity of firing: slight improvement; 5) operational reliability of solution: slight improvement.

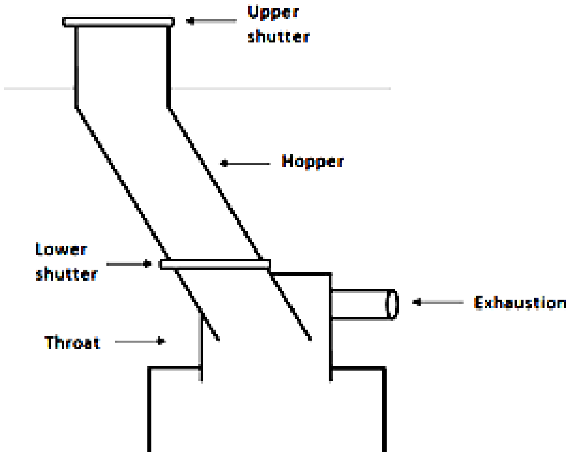

Fig. 7 Charging device proposal

3.2 Calcined anthracite charging

Non-uniform temperature distribution across the furnace cross section has a negative impact on the uniformity of the produced clinker quality.

The course of temperature along radius of the furnace workplace is relatively close to the maximum working lining and minimum in the very heart of the shaft furnace. The solution leading to a reduction in the size of the difference between T_{max} and T_{min} is implemented by appropriate technological fuel supply to the axis of the shaft furnace. It is necessary to ensure an adequate supply of combustion air and burning which is suitable for equalizing the temperature profile in the sintering furnace space. Calcined anthracite with an appropriate grain size is suitable additional fuel which is able to provide an increase in T_{min} in the shaft furnace axis in the sintering zone of the furnace.

Charging was carried out according to **Fig. 8**. An important prerequisite for obtaining desired effect of an increase in T_{min} at the shaft furnace axis was to ensure the specified quantity supply of calcined anthracite. Movement of anthracite charging was verified on a physical model at scale 1:10 (**Fig. 9**). The selected variants of anthracite use as a required supplemental fuel have been simulated using mathematical model. The results are shown in the **Table 4** and in **Fig. 10**.

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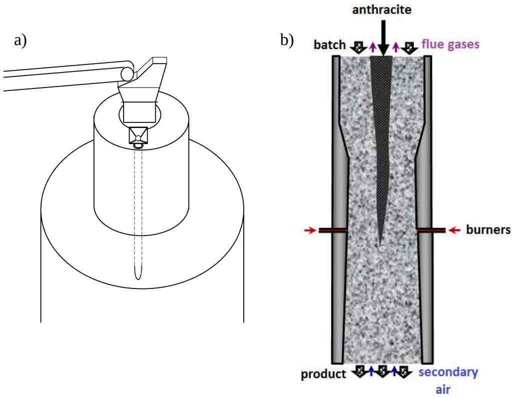

Fig. 8 Calcinated anthracite charging a) schematic of the method of the supplementary fuel dosing, b) material distribution

Fig. 9 Calcinated anthracite movement through the furnace physical model (scale 1:10)

Table 4 Mathematical simulation results

Alternative	Product [kg/h]	Batch			Natural [m^3/h]	Primary air [m^3/h]
		Anthracite [%]	Magnesite [kg/h]	Anthracite [kg/h]		
1	4750	3	6790	210	330	3400
2	4750	3	6790	290	360	3700
3	5000	3	7275	225	360	3700
4	5000	5	7125	375	360	3700
5	4750	4	6720	280	360	3700

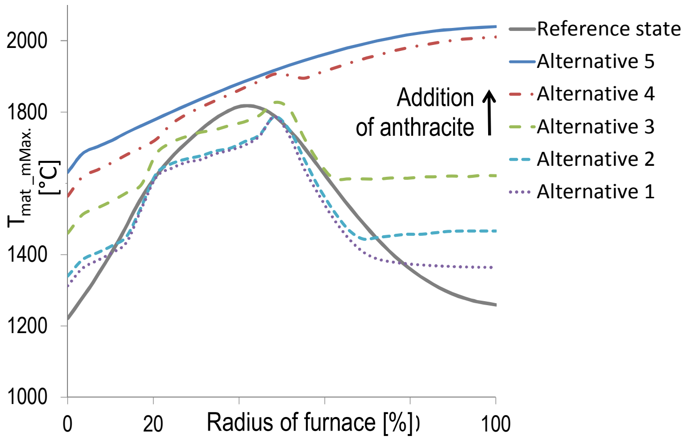

Fig. 10 Simulation comparision of reference and proposed alternatives

Calcined anthracite combustion in the shaft furnace axis will enable to use a large part of freely passing secondary air. This will lead to limit the total surplus of secondary air in the shaft furnace. Therefore, heat from fuel combustion will be used for the process of sintered magnesia

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production. Comparing the expected impact with reference state, the following changes have been occurred: 1) consumption of natural gas: improvement; 2) consumption of electric energy: improvement; 3) furnace performance: increase; 4) CO in flue gases: slight aggravation; 5) NO_x: slight improvement; 6) uniformity of firing: slight improvement.

3.3 Secondary air water addition

To solve an inhomogeneity problem of the temperature field in the sintering zone, it can be used a decrease in secondary air filling as a cooling media in the sintering zone of the shaft furnace. The point is to replace the secondary air volume by more effective cooling media - using the latent heat value of water vapour. Optimization of the shaft furnace operation is carried out by cooling media product to which water is added. The nozzles are suitable to use for this purpose. To reduce the total amount of flue gas in the furnace (limit factor of an increase in furnace capacity), it can be used the cooling effect of water added to the secondary air as an aerosol. The aim of the simulations (**Table 5**) was to find the amount of water added to the secondary air, so that the average temperature of the product on Grubber grade remained unchanged. The simulations were performed for the reference state, followed by gradual addition of water. The expected impact consist of an increase in the minimum temperature in the furnace axis by about 250°C, as well as a decrease in difference T_{max} and T_{min} in the shaft furnace, which will result in the increase in uniformity of firing quality and increase in the shaft furnace capacity by 1.6 % while maintaining the technological fuel volume. Comparing the expected impact with reference state, the following change has been emerged: 1) consumption of natural gas: - 1.6 %; 2) consumption of electric energy: slight improvement; 3) furnace performance: +1.6 %; 4) volume of waste gas: decrease; 5) uniformity of firing: slight improvement.

Table 5 Secondary air water adition simulation results

Alternatives	Furnace performance	V_{nozzle_water}	V_{cool_air}		Flue gases out				$T_{mat\ out}$
					T	V	O_2	H_2O	
	kg/h	l/h	m^3/h	l/min.	°C	m^3/h	%	%	°C
Alt.1 - Reference state (RS)	2417	0	1494	24900	255	7000	6	10	600.4
Alt.2 - RS+110l water	2417	110	1093	18217	243	6684	5	12	600
Alt.3 - RS+130l water	2417	130	1014	16900	240	6630	5	13	599
Alt.4 - RS+130l water + increased performance	2456	130	1014	16900	233	6650	5	13	602

4 Discussion

The basic requirement for a new shaft furnace is the possibility of the input magnesite processing in the range of granularity 20 - 40 mm. The significant benefit is the replacement of the rotary furnace by shaft furnace. Thereby a reduction in natural gas specific consumption by about 100 m^3/t of sinter could be achieved.

There are parallel solutions or extension possibilities.

- Reduction in specific fuel consumption can be achieved by using heat of sinter (heated secondary air can be used as a combustion air) and reduction in losses through the furnace shell.
- Heat losses can be reduced by increasing the insulation of the furnace shell.

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- A major impact on the reliability has the mechanical part of the furnace. The new concept of taking the sinter from the furnace has to enable replacement of the Gruber grate by four- stroke discharger.
- The heat generation distribution along a cross section of the furnace can be achieved by modification the burner system. This prevents the formation of conglomerates that have a significant impact on the reliability of the furnace operation and the sinter cooling.
- Reduction of CO and NO_x in the flue gases can be achieved by control of excess air and burning intensity by maximizing the primary flame.
- Distributed burning improves the quality of combustion at lower temperatures of combustion reducing the NO_x creation and thus can be achieved the reduction of the secondary flame proportion.
- The amount of flue dusts in the flue gas can be reduced by full use of secondary air for combustion. This will lead to reduce the average amount of flue gases per ton of the product.

5 Conclusion

Several innovative measures regarding dead burned magnesia production in the shaft furnaces based on a detailed system analysis of the magnesite firing process in the shaft furnaces and the latest results of research and development study and in particular the critical evaluation of current operational experience have been proposed. The innovative measures are not only beneficial for the shaft furnaces performance improvement. But using their application better understanding of the dead burned magnesite production process in the shaft furnace has been achieved. The paper deals with some selected measures. The acquired knowledge may then be used to design a new shaft furnace. The method of acquisition a new knowledge consisting in jointly solving the research and innovation tasks by academics and workers from business area enabling efficient generation and verification of new solutions is also very important. Such approach can serve as a model for the innovation process in the Slovak enterprises.

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