Proceedings of the 17th World Congress
The International Federation of Automatic Control
Seoul, Korea, July 6-11, 2008

Advanced process manipulation of magnesia sintering

Imrich KOŠTIAL, Ján SPIŠÁK, Ján MIKULA, Ján GLOČEK,
Pavol Nemčovský, Ján TERPÁK

Department of Applied Informatics and Process Control,
BERG Faculty, Technical University of Košice,
B. Němcovej 3, 042 00 Košice, Slovak Republic,
E-mail: imrich.kostial@tuke.sk

Abstract: Manipulation process is connecting of our macroscopic world to the microscopic or nanoscopic one. Manipulation can occur in a variety of ways. Outside manipulation take control over the process by external forces. Inside process manipulation is becoming a part of the process. This process manipulation is called advanced process manipulation (APM). Possibility of process manipulation may substantially enhance the process effectiveness. In this paper methods of advanced process manipulation are presented. An incremental manipulation process will be defined as a sequence of basic operations. Process manipulation generally requires custom-built system capable of performing of manipulation procedures. The progress in manipulation techniques can extend the application of the manipulated system. We have developed a simulation based system which was successfully implemented for designing of APM systems and control process in ways that are not conventionally possible. The developed system was applied on magnesia sintering process in shaft and rotary furnaces.

1. INTRODUCTION

Manipulation (Kostial et al., 2007, Lebiedz et al., 2003) is direct or indirect influencing of the process. Manipulation creates interface between the process and the user (Figure 1).

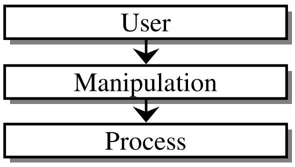

Fig.1. System of manipulation

Manipulation can be external, where process is influenced by outside forces, or internal, where process is influenced from inside by its interconnection with other processes. Being a part of the process APM allows doing things that are otherwise not possible as opposed to being separate process. According the manipulation mod we consider two basic approaches, outside – in approach and inside – out approach. Outside-in approach is user oriented. Process is forced to satisfy user objectives. Inside-out approach is process oriented. At this process driven approach process has dominant position and conditions have been created to realise it by the most natural way. Advanced process manipulation represents process oriented approach to the process manipulation. It is based on knowing process fundamentals, where all manipulation activities tend to satisfy the process optimally. This approach is bringing important changes to the process manipulation. However, presently in most of the solutions some regard is given to the process, but real process oriented approach is more exception than the rule. Existing individual solutions presents conceptual advantages of this approach and classical approaches can sustain only in some interconnection with these new conceptions. External manipulation is by domination of the object by the subject. Object is passive and is waiting on the intervention. At advanced process manipulation the object is active and requires minimum external force. Manipulation is executed by transformation, mutation and alteration. Process manipulation can be physical or logical (process activation, deactivation).

Process manipulation can be divided in the two categories: setting the attributes of a process, creating and managing the process. Manipulation theory is basic part of the control theory and serves as a background for manipulation processes. Process orientation means that key focus is on process needs. That means to have a system to be able to respond to the needs of the process. The whole system from process design to the process execution becomes increasingly sensitive what is happening in the process. It involves having keen sensors exploring the process state as well current and future trends. In essence process should drive our actions. Process orientation has different meanings. At each level process has to be optimal. Process orientation means to have right technology, right process organisation and right control system. Process orientation can be divided in two parts:

- Gather information from the process. Ability to understand process needs.

- Absorptive capacity – which is the ability to use this information to influence the process.

The willingness to meet the process needs means to be proactive to meet the process needs.

Process orientation is philosophy that optimises the realisation of the process potential. Process manipulation can produce significant improvement. One of the key factors of process orientation is process insight, which has two basic aspects:

- However complex the process may be we must to strive to understand it.

- There is number of sophisticated manipulation tools available to those who understand how to use them.

Our objective is to create unified approach to process optimisation with more powerful process manipulation by increasing feasible manipulation region.

2. PROCESS MANIPULATION MODEL

Process is influenced by two factors: macroscopic – external and microscopic – internal. Presented process manipulation model represents internal process manipulation philosophy and is based on hierarchical process model and on process optimisation.

2.1 Hierarchical process model

One of the dominant process relations are subordination and control. Each process is connected with some motion beginning with space displacement. Technological processes are expressed by state evolution in the time. Hierarchical process model (Kostial, 2002) is constructed on structural principles. It represents unified approach to different processes by using terms of general energy. In such way we can examine complex processes in genuine dynamics. At this base processes can be ameliorated. Hierarchical process model enables unified approach to process optimisation.

2.2 Process manipulation levels

Presented approach includes the following manipulation levels: structural level, organisational level, operational level and physical level.

STRUCTURAL LEVEL

At structural level optimal working device is determined. Structural measures assign process approach to the optimal one. The objective is to shift or remove the limitations and to create favourable conditions for process self – control. At structural level process is influenced by structural elements, their interconnections and parameters. Structural element allows manipulations of target process by becoming part of that process. It can manipulate, modify, process and control. It is to perform actions on behalf of the target process. Generally it is effective to transfer the manipulation elements on the local hierarchy levels. Local elements can execute relatively spontaneous form of operation with other units to meet changing demands. There is cross functional working - every single element must work to the same process oriented strategy. Often different elements are working to different strategies.

Process is influenced by structural - constant parameters and by variable technological quantities as temperatures and material composition. Introducing of process excitations increase process constant and consequently decrease apparatus effectiveness. Presence of stagnant zones, insufficient heat and mass transfer, limited flow conditions, process irregularities, cause qualitative process changes and disturbance of its time behaviour. Structural optimisation is at stationary working mode. Simple exponents express self-organisation lows of irreversible processes. Therefore it is required such mechanisms realising technological process according the exponential low with minimum external influence.

At structural level regularity of the relation working device-worked material and optimum of this behaviour is determined. Simple exponent is asymptotically stable function and can be the closure curve. It can be created by complex mechanisms which is basically not exponential. As exponential we can well express process without regarding its internal structure. Presence of exponential curves of process course is already sign about extremeness and self adjusting. Real processes are regularly realised under limitations. In those cases processes are expressed by more complex relations including simple exponents. In the case of limited resources the processes can be approximated by logistics curves. This curve has not such convenient proprieties as the simple exponent. Therefore we should accomplish process course by control inputs according the optimal trajectory.

ORGANISATIONAL LEVEL

Assures process approaching to the optimal one by selection of organizational forms determining the working regime. For determined structural level process optimum or its limits has to be find. Manipulation is to find a set of process trajectories that maps input state to the goal state. This mapping is governed by the lows of physics. All processes in the processing apparatus are harmonised.

OPERATIONAL LEVEL

Manipulation at this level is to determine a set of controls that maps current state to the desired trajectory. Operational level is created by external loops of input-output direct or indirect control. It is not possible to realise processes without disturbances. Disturbances are time functions. Process should run around selected trajectories. Controls stabilise planned trajectories. Controlled parameters are process parameters and product parameters. Controller or operator determines control parameters and is affected them on the processes. At his level control force F is determined

$$F= f\,(u_o - u)$$

Where u is control vector and $(u_o - u)$ is difference from the optimal trajectory.

Optimal strategy at this level is to stabilize process trajectory. Optimal working regime is achieved by control devices. It is preferred prediction instead of detection. External control is required for cardinal changes of process. It should be minimised.

PHYSICAL LEVEL

On physical level microscopic processes are realised. Microscopic processes determine macroscopic processes. Manipulation is to implement the controls by actuating physical devices governed by the lows of physics (motion, forces).This device works as transducers, accumulators, etc.

2.3 Process manipulation tools

APM presents advanced technology. Its purpose is to improve the control of the target process. The objective is to develop architecture for an internal manipulation system. Design of internal manipulation tools requires insight into the manipulation phenomena. For presented approach to the process manipulation a model based approach has been used. At theoretical analysis real technical system is replaced by some model which enables to regard system individualities. The best way is determination of complex state indicators. A surrogate modelling technique has been used (Kostial, Terpak, Mikula, 2006) by which the manipulation technique is predicted and optimised. The optimisation problem is solved using numerical programming methods. For solution of stated problem it is necessary to formulate ideal process and than to formulate more realistic models, define variables in which the model can be expressed and their relations. Model based optimisation has to the trial and error based experimentation the benefit of reducing this time exhaustive step while leading to the optimal solution. Via optimal strategy manipulation tools are generated.

3. MAGNESIA SINTERING PROCESS MANIPULATION

Magnesia sinter is a basic refractory material with high thermal resistance. Magnesia sintering process consists from calcinated magnesia porosity decreasing by its heating on the sintering temperature. Conversion of the input material to the sinter is realised by physical and chemical transformations. Production of magnesia sinter from magnesite ore includes the following operations: heating, calcinations, sintering and sinter cooling. Calcinations process begins at 399°C and is accomplished at the temperature near 900°C (Staron, Tomsu, 2000). The basic calcinations reactions are:

$$MgCO_3 = MgO + CO_2$$

$$CaCO_3 = CaO + CO_2$$

$$FeCO_3 = FeO + CO_2$$

Calcinated magnesia is then heated on the sintering temperature, which is above 1500°C.The sinter quality is determined by its density, which should be generally above 3 g/cm^3.Sinter quality can be influenced by sintering temperature and sintering time. Their interdependence is qualitatively represented on Fig. 2. By the proper choice of sintering conditions good quality sinter can be gained. Magnesia sintering is generally realised in shaft and rotary furnaces.

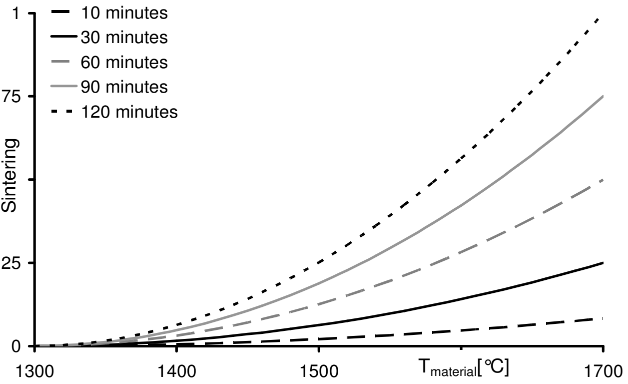

Fig.2. Sinter quality – sintering temperature and sintering time relation

3.1 Shaft furnaces

The shaft furnace for magnesia sintering is cylindrically shaped apparatus filled with vertically, in plug flow moving, thermally treated material (Fig. 3). Furnace is heated by wall burners with gas and primary combustion air. Secondary cooling air assures sinter cooling to the discharge temperature and generally is partly used as a combustion air. The cooling air has significant influence on the sintering process in the central part of the furnace (Fig.3).

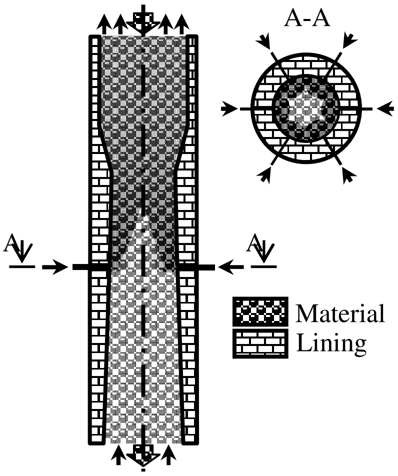

Fig.3. Shaft furnace for magnesia sintering

Sintering process in shaft furnaces is mainly influenced by inhomogeneity of the maximal sintering temperature (Fig. 4–reference process). This temperature profile is caused by gas flow through the material layer which is governed by Erguns equation (1). Erguns equation describes potential flow of gas through the packed bed.

$$\frac{\Delta P}{L} = aU + b\rho U^2 \qquad (1)$$

Where a and b are the properties of the packed bed and the fluid; ΔP is pressure drop; L is length of the bed (not the column); U is the superficial fluid velocity related to the void space; ρ is fluid density.

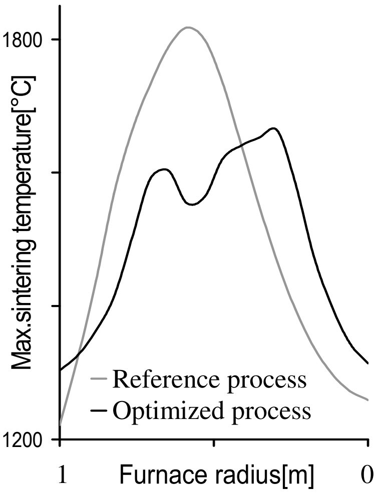

Fig.4. Distribution of maximal sintering temperature through the furnace section

Homogeneity of the maximal sintering temperature is principal factor influencing the furnace performance. When maximal sintering temperature is low, material is not sufficiently sintered. At high sintering temperatures the material becomes lumpy. Maximal sintering temperature distribution was internally influenced at structural level by integrated approach consisting from: charge granulometry redistribution, combustion process reconfiguration, increasing the heat transfer intensity and from decreasing of the furnace heat losses.

Charge granulometry influence the charge permeability. Its distribution can be manipulated by charging device modification (Fig.5).

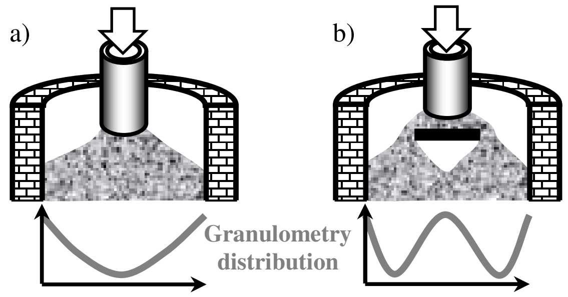

Fig.5. Charging device modification

At the present charging device the lowest granulometry is in the central part of the furnace, which negatively influences its permeability (Fig.5a). By reconfiguration of the charging device significant improvement of the charge granulometry distribution was achieved (Fig. 5b).

Combustion process reconfiguration: Present burners (Fig. 6a) have central fuel input and peripheral primary air input. Heat generation is distributed according the Fig. 7a. This configuration creates high maximal temperature inhomogeneity through the furnace cross section and prevents effective combustion of the secondary air. Combustion process reconfiguration includes relocation of the fuel input from the burner centre to the burner periphery and two layers burners' arrangement with lower layer burners inserted into the central part of the furnace (Fig.7b). By this rearrangement convenient conditions for the secondary air combustion were created and the distribution of the heat generation and consequently the temperature distribution through the furnace cross section was significantly improved (Fig.4).

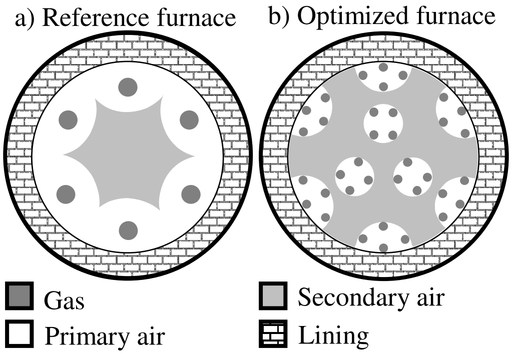

Fig.6. Shaft furnace media flow distribution

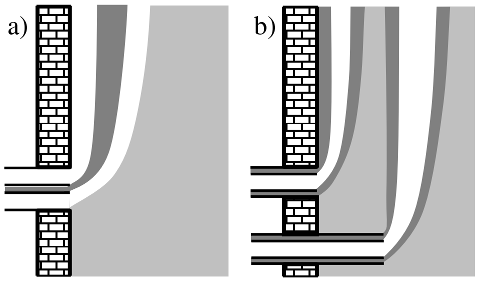

Fig.7. Combustion process reconfiguration

3.2 Rotary furnaces

The rotary furnace is schematically presented on Fig.8.

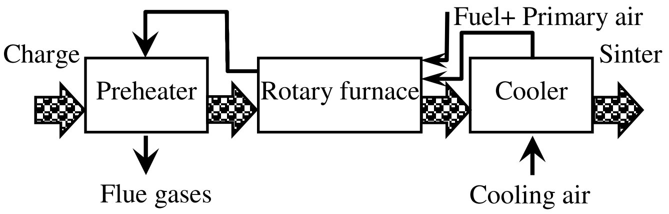

Fig.8. Rotary furnace arrangement

The row material, charged in to the furnace, creates a bed which is moved through the furnace by its revolutions (Fig.9).

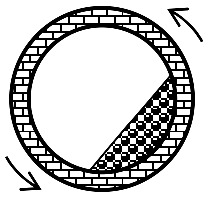

Fig.9. Rotary furnace cross section

The main disadvantage of the rotary furnaces is their high specific fuel consumption. Because of process limitations it can not be improved by operational measures. For the process improvement the following internal manipulation elements were developed: charging device, diffuse burner, charge preheater and sinter cooler, furnace shell controlled cooler.

The charging device (Fig.10) has two basic functions: charging of the material into the furnace and increasing of the material layer thickness. Material layer thickness influences the sintering temperature homogeneity and the sintering time. Material movement mod in the sintering bed depends on the layer thickness. At low layer thickness the material is sliding over the furnace lining without remarkable mixing. Material inside the layer is heated mainly by the heat conduction. Created temperature inhomogeneity is denoted as kidney effect. At layer thickness above the critical value, the material is mixing inside the layer and consequently the temperature homogeneity is increasing.

Sintering time depends also on the material layer thickness. With higher layer thickness the sintering time is increasing. The layer thickness influence too the fuel consumption, heat transfer, utilisation of sinter heat, flue gas and furnace heat loses.

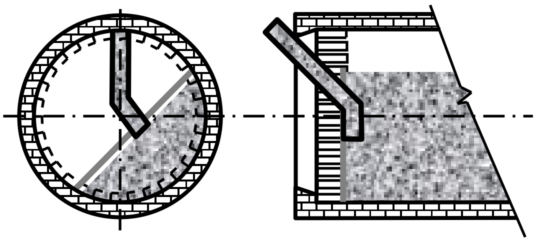

Fig.10. Rotary furnace charging device

Charging device is conceived upon internal control principals. Fig. 11 presents comparison of material level control by external and internal manipulation.

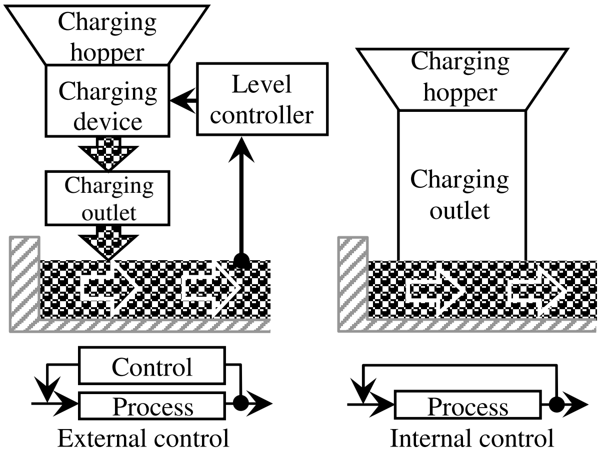

Fig.11. External and internal material level control in the rotary device

Diffuse burner combustion system (Fig.12) by its configuration enables effectively combust preheated secondary – cooling air, to adjust the flame length and to intensify the heat transfer by the flame rectifying on the material layer surface.

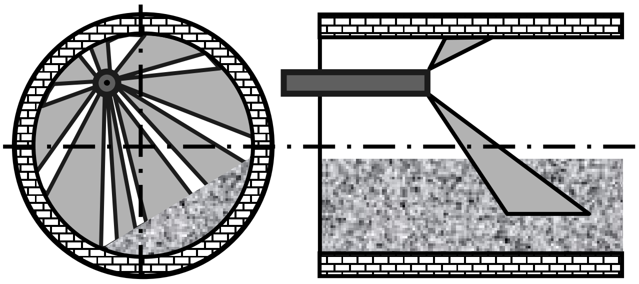

Fig.12. Diffuse burner combustion system

Heat transfer intensification has significant influence on furnace performance. The developed cross flow heat transfer processing element can intensify the heating and cooling process. It can be also integrated into the rotary part (Fig.13).

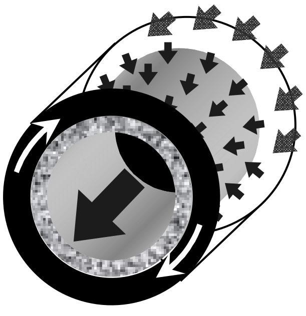

Fig.13. Heat transfer element

By these modifications the sintering process is running near its technological optimum (Figure 14)

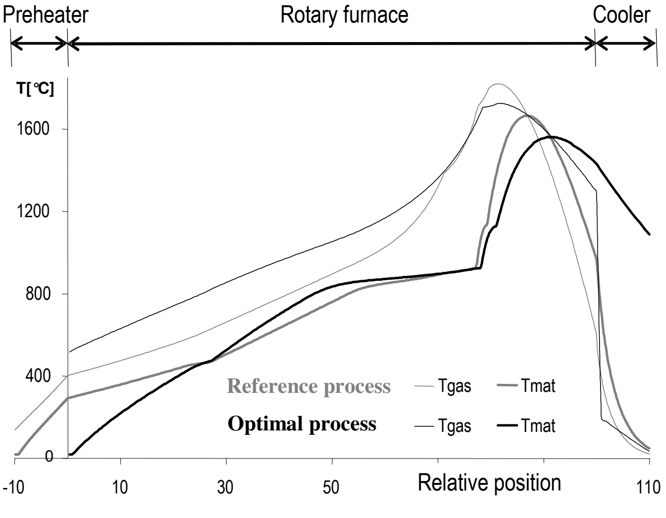

Fig.14. Rotary furnace sintering process trajectory

3.3 Control system

Organisational and operational process manipulation levels are realised in the framework of the control system. At the organisational level optimal process trajectory and its responding fuel input is determined. The process trajectory is calculated for the given furnace throughput, charge composition and required sinter quality by stationary process model. The sinter quality is calculated according the relations on Fig.2. When more then one charge quality or required sinter quality are simultaneously in the furnace, the optimal process trajectory is responding to the most critical charge.

Contemporary control system is realised on the operational level (Fig.15). The sintering temperature is determined according the sinter quality. Required sintering temperature is controlled in the feedback loop by the fuel or charging material input. Proposed operational level is feed forward - feedback. The actual process trajectory is determined according the process disturbances by the dynamic process model. Control input is corrected for the critical charge and for the actual and required sintering temperature differences (Fig.16).

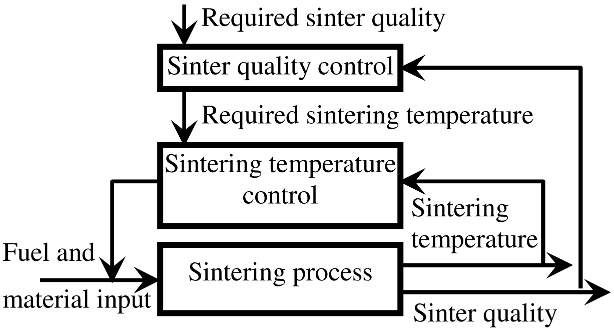

Fig.15. Sintering process contemporary control system

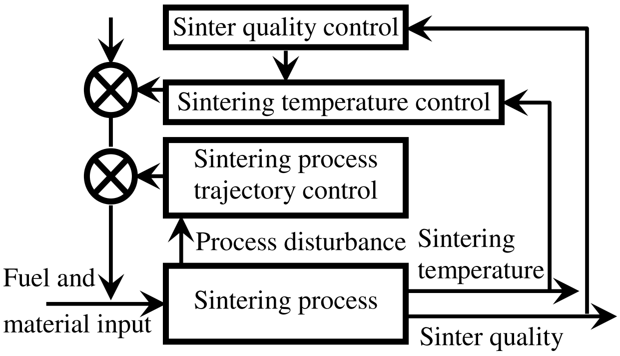

Fig.16. Designed sintering process control system

3.4 Practical results

Internal process manipulation modules of the shaft and rotary furnaces have been tested at laboratory scale. On digital model was simulated impact of individual manipulations modules as far as their integration into the unique apparatus. The application is oriented on particular equipments in the Slovak magnesia industry.

The working rotary furnace was equipped with charging device. In the presented case the charging material level was increased from 40 to 130 cm. By the internal material level control external level controller based on weighting of charged material was replaced. By increased material level thickness exhausted dust quantity has decreased up to 30 % and 6 % fuel economy was achieved.

For shaft furnaces the laboratory scale experiments and digital simulations have shoved significant influence of burner construction and burners arrangements on the sintering process. Plant scale experiments have proved these results.

4. CONCLUSIONS

Progress in manipulation technique creates new field in control engineering. Manipulation theory can offer better ground for process manipulation. APM can improve process design, process management and deployment of process tailored operations.

Process manipulation enables more precisely control of magnesia sintering. Structural level has substantial impact on the fuel economy. Organisational and operational level enables more precisely adjust sintering conditions during the sintering process and enhance the sinter quality. Model based optimisation ameliorates this time exhausting step based on trial and error experimentation. Created tools can significantly improve the magnesia sintering process performance. Achieved results are closely to the technologically optimal limits. For the treated shaft furnaces the specific fuel consumption can be reduced as much as 20% and for the rotary furnaces as much as 40 %.

ACKNOWLEDGEMENTS

This work was partially supported by grant VEGA 1/2160/05, 1/2179/05, 1/2167/05 and 1/3132/06 from the Slovak Grant Science Agency; by grant APVV-20-061905 from the agency for Research and Development Support; by grant AV 4/0001/07 from the Ministry of Education of Slovak Republic and by grant 2003 SP 26 028 0C 01 from the National Programme #4.

REFERENCES

Kostial, I. (2002). *Process theory*, 86 p. Technical University of Košice, Košice.

Kostial, I., Terpak, J. and Mikula, J. (2006). *Surrogate modelling of processes fo granular material thermal treatment*, pp. 161–166, IFAC WORKSHOP MMM´2006, Cracow – Poland.

Kostial, I., Terpak, J., Spisak, J., Mikula, J. and Glocek, J. (2007). *Advanced process manipulation,* pp. 342–354, 8th International Carpatian Control Conference. Strbske Pleso-Slovak republic

Lebiedz, D. and Brandt-Pollmann, U. (2003). *Manipulation of Self-Aggregation Patterns and Waves in a Reaction-Diffusion* System *by Optimal Boundary Control Strategies*, pp. 208301-1- 208301-4, Physical review letters. VOLUME 91, NUMBER 20.

Staron, J. and Tomsu, F. (2000). *Refractory materials, their production, properties and application*, 445p., SLOVMAG Lubenik, Lubenik