RIGA TECHNICAL UNIVERSITY
Civil Engineering Department

Vjačeslavs LAPKOVSKIS
Doctoral BDS0 programme

CONVEYING OF FERROMAGNETIC POWDER MATERIALS BY IMPULSE ELECTROMAGNETIC FIELD

Summary of Doctoral Thesis

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APSTIPRINĀJUMS

Apstiprinu, ka esmu izstrādājis doto promocijas darbu, kas iesniegts izskatīšanai Rīgas Tehniskajā universitātē inženierzinātņu (vai cita) doktora grāda iegūšanai. Promocijas darbs nav iesniegts nevienā citā universitātē zinātniskā grāda iegūšanai.

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Promocijas darbs ir uzrakstīts angļu valodā, satur ievadu, 5 nodaļas, secinājumus, literatūras sarakstu, 6 pielikumus, 51 zīmējumus un ilustrācijas, 9 tabulas kopā 114 lappuses. Literatūras sarakstā ir 119 nosaukumi.

TABLE OF CONTENTS

1 GENERAL CHARACTERISTICS OF THESIS

1.1 TOPICALITY OF THESIS

- Modern manufacturing processes require different specific approaches for transportation of various bulk materials, including ferromagnetic ones.
- Ferromagnetic materials (metal powders, chips, small metallic parts (e.i. nuts), ferrous dross, ores) can be conveyed by means of pneumatic or mechanical conveyors (screw, plate, bucket conveyors). One of perspective solution - use of impulse electromagnetic fields for conveying of ferromagnetic materials, including ferromagnetic powders and powder parts.
- The use of pulsed electromagnetic fields for conveying of ferromagnetic materials is especially important for powder metallurgy and complementary industries, for improving efficiency of technological processes related to the conveying of fine powder materials.
- The use of impulse power sources (impulse magnetic fields, in particular) in powder metallurgy is relevant, as it facilitates development of new technological processes, such as compaction, forming, and sintering of powder materials.

1.2 AIM OF THESIS

The research of phenomena of conveying of ferromagnetic materials by impulse electromagnetic field and its implementation, definition of process parameters and their influence on the process.

1.3 TASKS OF THESIS

- Review of information on continuous transport systems of ferromagnetic materials, powder and powder parts and their characterisation.
- Development of experimental low-voltage equipment for process research.
- Development of measurement system for process parameters and its evaluation.
- Development of process modelling approaches of the conveying of ferromagnetic materials by impulse electromagnetic field.
- Elaboration of further recommendations for applications of conveying by impulse electromagnetic field.

1.4 SCIENTIFIC NOVELTY OF THESIS

- The principles of the conveying process of dispersed materials by impulse electromagnetic field are developed.
- A model of the process of moving a ferromagnetic powder material in a impulse electromagnetic field is suggested.
- A technique of measurement of parameters of impulsed process for conveying of ferromagnetic materials is developed.
- It was found that one of the important parameters is the distance between the coil and the surface of the powder (ferromagnetic material), which provides a maximum efficiency of the process.
- The influence of the materials weight, dispersion, and properties of the material on the performance and range of transportation is established.
- The influence of process parameters on the efficiency of

material conveying is evaluated.

1.5 PRACTICAL VALUE OF THESIS

A possibility of powder conveying by impulse electromagnetic field in different environments (media) and directions has been shown. This is confirmed by co-authoring of several national patents.
The model of the device, which made it possible the long-term experimental study has been designed and manufactured. The design has been presented in a number of conferences and exhibitions in Latvia and abroad.
On the basis of experimental studies, areas of practical application were identified (powder metallurgy, civil engineering, machinery engineering).
The principles of equipment design were developed.
As a research result, a number of experimental devices (for dosage, vertical conveyor, mixer, and for pressing) have been designed.

1.6 METHODS OF THE RESEARCH

Using the FEA modelling software (FEMM and Lua scripting language), the thesis studied the phenomenon of ferromagnetic powder materials conveying by pulsed electromagnetic field. Main parameters of conveying process have been defined. For mathematical processing of obtained data LibreOffice and SciDavis software have been used, together with developed slow-motion video recording and analysis system (using Avidemux software on Linux). Experimental research of the conveying process by impulse electromagnetic field has been realised by means of designed low-voltage (up to 1000 V) laboratory set-up.

1.7 MAIN RESULTS OF THE THESIS

1. A physical model of conveying of ferromagnetic powder materials (ferrous powders) in vertical pipes by pulsed electromagnetic field

has been developed.
2. A FEA research model for interaction between ferromagnetic powder materials and electromagnetic field has been developed by means of FEMM and LUA software for finite element analysis.
3. A low-voltage laboratory installation (up to 1000 V) for conveying of ferromagnetic powder materials in vertical pipes (up to 2 m height) and maximum throughput 2-3 t/h has been designed.
4. Ferromagnetic powder materials throwing and mixing techniques in different media by means of impulse electromagnetic field have been developed and verified for laboratory conditions. The developments are confirmed by Latvian national patents LV14382(B) and LV14383(B).
5. It was found that suggested method can be used for conveying of ferromagnetic powders and granular materials with a wide particle size range (from 20 μm up to 10 mm).
6. Prospectives of powder material mixing and blending techniques have been shown.

1.8 COMPOSITION AND VOLUME OF THESIS

Doctoral thesis contains 5 chapters, conclusions and references. Thesis volume includes 114 printed pages, 51 figures, 9 tables and bibliography containing 119 titles.

1.9 APPROBATION AND PUBLICATIONS OF THESIS

Results of this doctoral thesis have been reported and discussed at the following international conferences:

1. V. Mironov, J. Viba, and V. Lapkovsky, "Lifting of disperse materials with pulse electromagnetic field." *Nanomaterials and Nanotechnologies (NENAMAT-2005), Riga, Latvia*, 2005.
2. V. Mironovs, J. Viba, and V. Lapkovskis, "Investigation of impulse system for moving powder materials in vertical pipe," *1st Int. Conference on vibro-impact systems ICoVIS*, Loughborough, UK, 2006.
3. V. Mironov, I. Boyko, and V. Lapkovsky, "Intensification of

manufacturing processe by transportation of bulk materials by a pulsed magnetic field / In Russian/," *Powder materials and processes of their production*, Minsk, Belorus, 2008.

4. V. Mironov, J. Viba, and V. Lapkovsky, "Electromagnetic transportation of ferromagnetic powders in pipes /in Russian/," *Poroshkovaya metallurgiya*, Minsk, Belorus, 2010.
5. V. Lapkovsky, V. Mironovs, A. Shishkin, and Zemch, "Conveying of Ferromagnetic Powder Materials by Pulsed Electromagnetic Field," *EuroPM-2011, Barcelona, Spain*, 2011.
6. V. Lapkovskis and V. Mironovs, "Single-stage Electromagnetic Elevator Modelling in FEMM software," *8th International DAAAM Baltic Conference "Industrial Engineering", Tallinn, Estonia,* 2012.
7. V. Lapkovsky and V. Mironov, "Conveying of ferromagnetic powders by impulse electromagnetic field," in 5th International Conference on High Speed Forming ICHSF-2012, Dortmund, Germany, 2012.

A Thesis work has been discussed in the following scientific seminars:

a) At a meeting of the Board of the Scientific Laboratory of Powder Materials at RTU (2010-2012)
b) At a meeting of RTU, Civil engineering dept. (2011)
c) At a scientific seminar RTU, SGUTI institute (2010-2012)
d) At a seminar in the IFAM Fraunhofer, Dresden (2011)
e) At a seminar in the University of Applied Sciences of Zwickau (Germany) (2011)
f) At a scientific-industrial conference ICHSF-2012 on high-speed electromagnetic forming at Institut für Umformtechnik und Leichtbau, in Dortmund (Germany) (2012)

In the period of 2005-2012 totally 30 publications have been published. The most important are:

<u>in journals and conference proceedings:</u>

1. V. Mironov, J. Viba, and V. Lapkovsky, "Lifting of disperse materials with pulse electromagnetic field," in *Nanomaterials and Nanotechnologies (NENAMAT), Riga, Latvia*, 2005, pp. 118-120.
2. V. Mironovs, J. Viba, and V. Lapkovskis, "Investigation of

impulse system for moving powder materials in vertical pipe," in *Book of abstracts of the1st Int. Conference on vibro-impact systems*, 2006, p. 30.

3. V. Mironov, I. Boyko, and V. Lapkovsky, "Intensification of manufacturing processe by transportation of bulk materials by a pulsed magnetic field / In Russian/," *Powder materials and processes of their production*, vol. 31, pp. 101-104, 2008.
4. V. Mironov, J. Viba, and V. Lapkovsky, "Electromagnetic transportation of ferromagnetic powders in pipes /in Russian/," *Poroshkovaya metallurgiya*, vol. 33, pp. 53-59, 2010.
5. V. Lapkovsky, V. Mironovs, A. Shishkin, and Zemch, "Conveying of Ferromagnetic Powder Materials by Pulsed Electromagnetic Field," in *EuroPM-2011 – Tools for Improving PM: Modelling & Process Control*, 2011, pp. 253-258.
6. V. Lapkovskis and V. Mironovs, "Single-stage Electromagnetic Elevator Modelling in FEMM software," in *8th International DAAAM Baltic Conference "Industrial Engineering,"* 2012, no. April, pp. 321-325.

<u>in exhibitions:</u>

1. EuroPM-2010, International Conference and exhibition, Florence, Itālija.
2. Izgudrotāju diena 2010, 2011, Rīgas Tehniskā Universitāte, Rīga, Latvija
3. Tech Industry 2011, Pulvera materiālu transportēšana ar impulsu elektromagnētisko lauku,, Rīga, Latvija
4. V. Lapkovsky and V. Mironov, "Conveying of ferromagnetic powders by impulse electromagnetic field," in 5th International Conference on High Speed Forming ICHSF-2012, Dortmund, Germany, 2012.

2 STRUCTURE OF THESIS

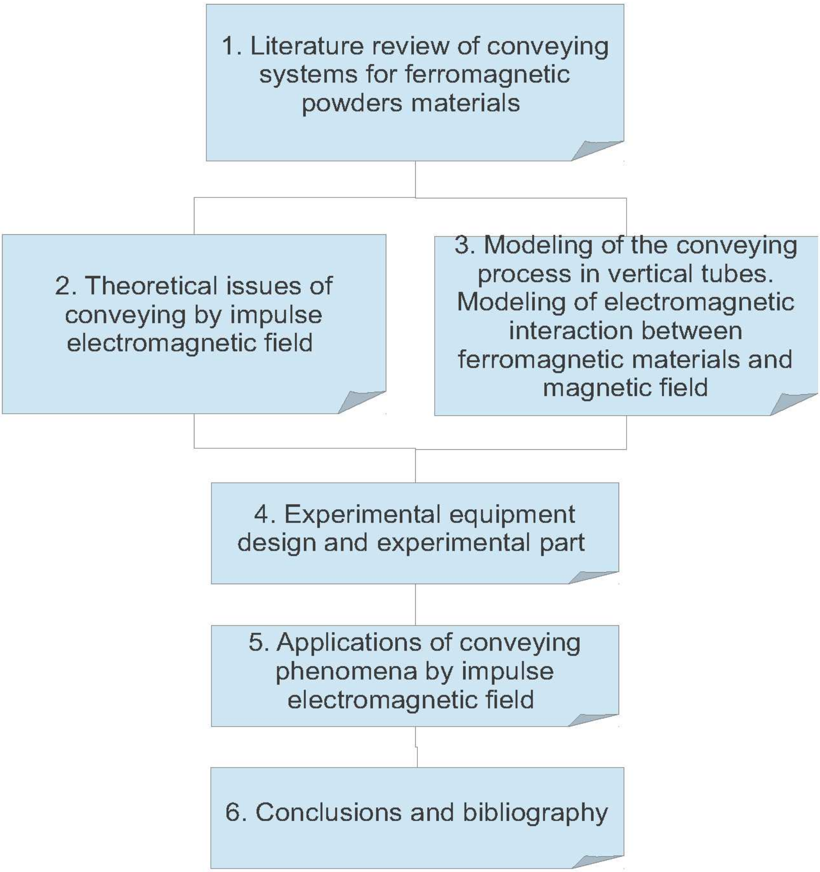


Figure 2.1: A flow chart of Thesis structure

3 CONTENTS OF THESIS

3.1 FIRST CHAPTER. LITERATURE REVIEW OF CONVEYING SYSTEMS FOR FERROMAGNETIC POWDERS MATERIALS.

This chapter examines information sources on conveying of ferromagnetic powder materials and information regarding electromagnetic conveying of ferromagnetic powders by impulse electromagnetic field.

Ferromagnetic powder materials [1] are extremely important for a variety of powder parts manufacturing processes at almost all manufacturing stages [2], [3]. The most common operations where conveying of powdered materials is taking place (Figure 3.1.1) are: vertical, horizontal and inclined transportation, dosage, loading to and unloading from containers [4], [5]

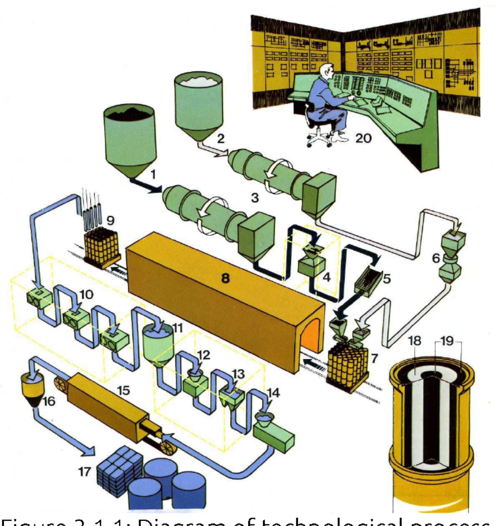


Figure 3.1.1: Diagram of technological process of sponge iron powder production (Hoganas AB)

Dr Johnston is emphasizing, that especially great energy and labour-consuming costs occur in organizing the production of ferromagnetic powders and mixtures [6]. In these cases powders

are transported for crushing, annealing, separation, and for other operations [7]. Mechanical and pneumatic conveying systems are widely used for transportation of powdered materials, including ferrous or iron powders. D.Mills in his book reports [8] that high pressure pneumatic systems are suitable for conveying of iron powder with apparent density of 2.4 g/cm^3. This method has a drawback because it is not suitable for heavy powders due to high pressure needed for transportation of heavy particulates.
Prof. Romakin in his book [9] describes chain and bucket conveyors for use in continuous transport systems. Several European companies Idealtec Powder (Italy) and Schrage Rohrkettensystem GmbH have developed a particular chain conveyors for powders, including ferrous powders and ores used in manufacturing of graded iron powders [10], [11] Two drawbacks of suggested conveying systems can be noted, one of them is a large steel capacity for construction, and an intensive wear of construction materials.
Kurjak in her work analyses vertical screw conveyors for ferromagnetic powders transportation, which represents a traditional approach for conveying of iron powders [12] The method is mostly used at short transportation distances and characterises by great wear of construction materials.
At Riga Technical University (Latvia) a research of treatment by impulse electromagnetic fields of ferrous and non-ferrous materials mainly was tied to metallic and non-metallic powder pressing and treatment of powder compacts by pulsed electromagnetic fields [13]. A particular area of interest was the development and manufacturing of generators of impulse currents, and coils suitable for pressing and deformation of powder materials.

Thank to continuous demand from the industry, a study of new methods of ferromagnetic materials transportation has been started at Riga Technical University ([14]).
A hypothesis of ferromagnetic materials transportation by electromagnetic field has been formulated in Riga Technical University by Prof. Mironov et al. [15] subsequently developed by Prof. Mironov and Prof. Viba [16]

Current Thesis work is dedicated to the research of phenomena of ferromagnetic powders conveying by impulse electromagnetic field and its implementation, definition of process parameters and their influence on the operating efficiency.

3.2 SECOND CHAPTER. THEORETICAL ISSUES OF CONVEYING BY IMPULSE ELECTROMAGNETIC FIELD.

In this chapter, a theoretical background of conveying by impulse electromagnetic field is given. Generators of impulse currents and coils used in laboratory equipment design are presented.

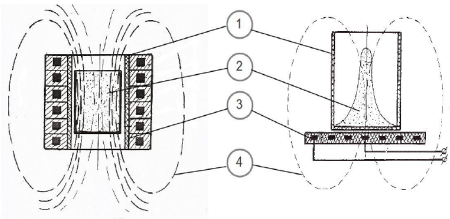


Figure 3.2.1. Moving a powder by electromagnetic field.

1 – tube used for conveying of ferromagnetic material, 2- ferromagnetic material, 3 – coil, 4 – electromagnetic field lines

A behaviour of ferromagnetic materials in magnetic fields is well-known and is used in a variety of applications [17] There are many technical applications of materials treatment by electromagnetic field. Some of them are: magnetic-abrasive machining [18], magnetization and demagnetization of materials [19], thermomagnetic hardening [20]) . Process of powder conveying (Figure 3.2.1) can be expressed as as a movement of the determined centre of mass under the influence of pulse pressure (Figure 3.2.2). A force which provoke a displacement of ferromagnetic material is an electromagnetic force F_m which can be determined by the following equation (3.1)

$$F_m = \mu_0 \mu \ k \left(\frac{|i(t)|}{n} \right) \frac{r}{z} \quad (3.1)$$

where:

μ_0 - permeability of vacuum, μ - permeability of powder, k – factor coil-powder, $i(t)$ - coil impulse current, n – a number of coil turns, r - mean radius of winding, z – a gap between winding and a ferromagnetic material

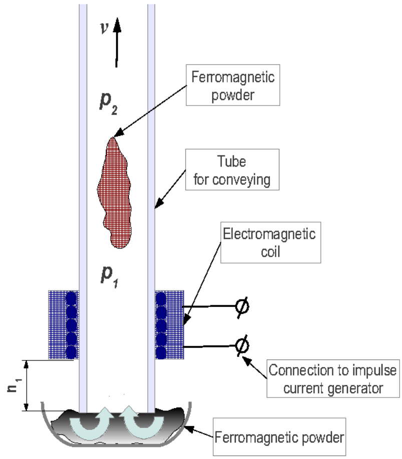


Figure 3.2.2 Schematic of powder conveying by impulse electromagnetic field.

The peculiarity of electromagnetic acceleration process is based on the effect of a short electromagnetic impulse. At a time of its termination (milliseconds) a ferromagnetic material continues its movement (lifting) through the acquisition of inertia. The important parameters of impulse are the following: an amplitude, duration, and damping rate.

In this case, coil is primary circuit, which is inductively connected to a lifted body (a ferromagnetic powder), which acts as a secondary circuit. Discharging of a capacitor to the coil inductor current flowing in the primary circuit, excites the eddy currents in the secondary circuit. The coil and the lifted body induce a magnetic fields in two opposite directions. This leads to rapid rising of ponderomotive forces [21], due to a lifted body acquires an initial velocity. So energy of capacitors is converted into the energy of magnetic field inducer, and then into mechanical energy of powder thrown from the coil's electromagnetic coupling zone, and partially into heat.

3.3 THIRD CHAPTER. MODELING OF THE CONVEYING PROCESS IN VERTICAL TUBES.

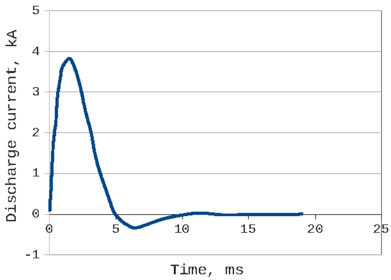


Figure 3.3.1: Impulse current plot vs time.

In this chapter, a modelling of conveying by impulse electromagnetic field, modelling of interaction between ferromagnetic materials and magnetic field.
In current thesis a model of electromagnetic conveyor is proposed. A model of conveying system can be described as one second order differential equation for motion (3.2) of centre of mass of porous body [22] (Figure 3.3.2).

$$m\ddot{x} = p_1 S_1 - p_2 S_2 - mg - F_T - C_0 (\Phi)^2 \, sgn\, x \qquad (3.2)$$

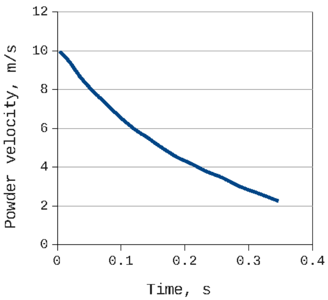


Figure 3.3.2: Powder velocity plot in time domain

where x - displacement of centre mass; m - conveyed mass; p_1, p_2 - pressure below and above moving powder; S_1, S_2 - corresponding areas; g - acceleration of free fall; F_T - friction force between tube and powder; Φ - magnetic flow; C_0 - coefficient.
For pressure p_1, p_2 calculation, a theory of pneumatic systems has been used [23]
Respectively, a discharge current

of coil influences on magnetic force or magnetic blow. In the first approximation discharge current $i(t)$ of inductor can be expressed in the following form (3.3).

$$i(t) = I_m \cdot e^{-\alpha t} \cdot \sin(\omega t) \tag{3.3}$$

Where I_m, α - constants; ω - angular frequency of discharge current, which can be described by the following equation (3.4).

$$\omega = \sqrt{\frac{1}{LC}} \tag{3.4}$$

where L – an inductive resistance of discharge circuit, C – a capacity of condensers in discharge time. An impulse current plot in time domain is shown in (Figure 3.3.1).

A further modeling has shown that the equation of motion (3.1) can be transformed and separated into two steps which include modelling of rapid process for magnetic circuit with small displacement of powder by expression for engineering calculation (3.5):

$$m\ddot{x} = p_1 S_1 - p_2 S_2 + F_m \tag{3.5}$$

A modelling of powder velocity in time domain is plotted in (Figure 3.3.2).

Here, an interaction between ferromagnetic material and electromagnetic field is of importance for understanding of material transportation phenomena. Therefore, a modelling of electromagnetic field distribution and evaluation of

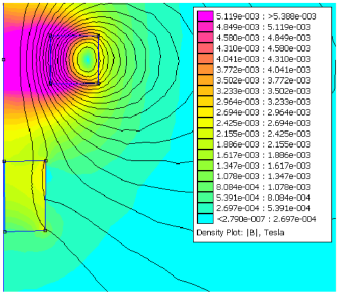


Figure 3.3.3 Magnetic field density plot for Coil(01). At starting point.

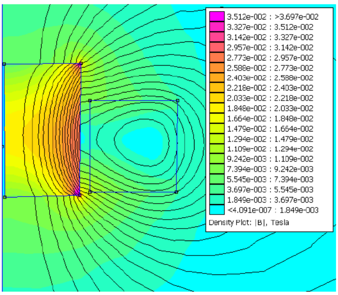


Figure 3.3.4 Magnetic field density plot (in Tesla) for Coil(01). In the last point.

electromagnetic force effected to ferromagnetic material has been done by mean of FEMM software and LUA script language [24].
The following assumptions of FEMM model have been taken into account: steady current (in coil), no eddy currents, simulation for every position (shift) of powder body along the Z axis is calculated for the steady-state conditions.

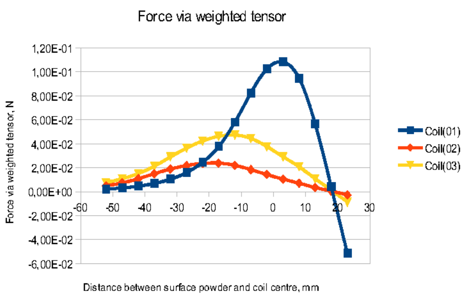


Figure 3.3.5 Magnetic field force acting on ferromagnetic material vs distance from the coil

Changes of magnetic field density in starting and in final locations of ferromagnetic body for for Coil No 1 (Coil(01)) are shown in (Figures 3.3.3 and 3.3.4). A script written in LUA performs a step-shifting of powder body along a z-axis with following numerical analysis and calculating z-directed component of force for every position of powder body (Figure 3.3.5).
Research results and elaborated techniques can be used in further engineering tasks.

3.4 FORTH CHAPTER. EXPERIMENTAL EQUIPMENT DESIGN AND EXPERIMENTAL PART.

This chapter covers an experimental research of conveying by impulse electromagnetic field process.

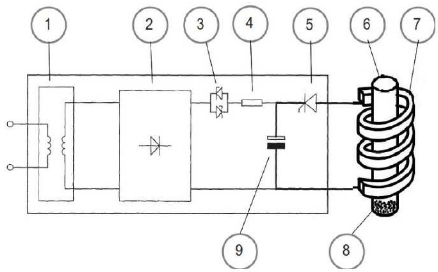


Figure 3.4.1 Schematic of EMC-05 electro-magnetic conveyor.

1 – transformer, 2 – rectifier, 3 – triac (thyristor), 4 – charging resistor, 5 – dis-charging thyristor, 6 – conveyor tract (tube), 7 – coil, 8 – ferromagnetic powder, 9 - capacitor battery.

Figure 3.4.2 RTU EMC-05 laboratory-scale electromagnetic elevator.

Thanks to support, provided by the European Social Fund for Doctoral studies at Riga Technical University, a laboratory-scale equipment EMC-05 [25] for conveying of ferromagnetic powders has been designed (Figure 3.4.2). Use of low-voltage equipment (< 1000 V) is a peculiar feature of presented experimental installation.

A device for the electromagnetic powder conveying comprises: a generator of impulsed current (GIC), a pipe for powder transport, and inductor (coil), which forms a directed electromagnetic field. Schematic of the device is shown in (Figure 3.4.1).

A set of tools has been adapted for process parameters measurement. Among them: the measurement of pulsed current using Rogowski coil [26] and the use of slow-motion video for controlling the movement of powder.

A set of commercially available ferromagnetic powders [27] [28] has been used for tests (Table 3.4.1). CMS powder and iron dross have been chosen for comparative purpose as they differ from graded iron powders. Four cylindrical coils with different winding lengths made of aluminium and copper insulated wire have been prepared (Table 3.4.2).

Table 3.4.1: Ferromagnetic powders used in laboratory-scale experiments

Ferromagnetic powder material	**Particle size range, μm**	**Fe conten t, %**	**Apparent density, g/cm³**	**Short deescription**
NC100.24 (Hoganas powder)	20-180	~99.9	2.45	Pure sponge-iron grade powder
ASC100.29 (Hoganas powder)	20-180	~99.9	2.98	Pure water-atomized iron powder
M20/80-19 (Hoganas powder)	40-200	~99	2.60	Carbon-reduced sponge iron powder
Somaloy 500 (Hoganas powder)	50-100	~95	3.20	Isotropic high-purity iron powder
Distaloy AE (Hoganas powder)	50-100	~95	3.05	Diffusion alloyed iron powder
CMS powder (filter sediments from Hoganas production facility)	10-60	~99	2.85	Combination of different iron powders
Fe dross (powder)	50-200	~65-69	2.30	Mixture of iron oxides and iron powder

Table 3.4.2: Coils used in experimental research.

Coil No.	**Winding material**	**Coil dimensions width, height, mm**	**Wire diameter, mm (with insulation), mm**	**Electrical conductivit y of winding material, MS/m**	**Number of turns**	**Coil inductance , μH**
01	Cu wire	25 x 25	5 (7)	59.6	9	132
02	Al wire	25 x 90	4.5 (7.5)	35	30	197
03	Cu wire	40 x 75	3.5 (5.5)	59.6	12	164

Coil No.	Winding material	Coil dimensions width, height, mm	Wire diameter, mm (with insulation), mm	Electrical conductivity of winding material, MS/m	Number of turns	Coil inductance, µH
04	Al wire	75 x 40	4.5 (7.5)	35	16	71

A number of coils for conveying of ferromagnetic powders have been designed. One of coils used in experiments is presented in Figures 3.4.4 and 3.4.3.

Figure 3.4.4: Coil(01), winding: Cu wire.

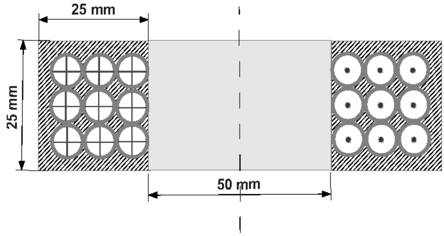


Figure 3.4.3: Schematic of Coil(01) winding.

Different parameters influencing on performance of electromagnetic conveyor have been evaluated:

- A relationship between discharge energy and amount of transferred powder material for conveying heights up to 1.5 m (Figure 3.4.5).
- an influence of coil geometry (and wire material) to elevating power for different powder materials.
- an influence of distance between coil surface (bottom side) and surface of powder material (Figure 3.4.6).

A relationship between discharge energy and amount of conveyed material is analysed for low-energy laboratory-scale conditions. An amount of powder conveyed in single impulse is shown in (Figure 3.4.5). The following test trials (Figure 3.4.6) of different ferromagnetic materials have demonstrated a strong dependence between maximum lifting height and a distance between electromagnetic coil and surface of ferromagnetic powder.

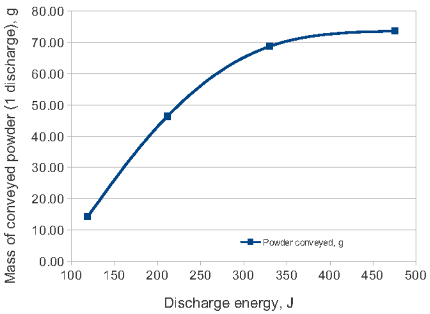


Figure 3.4.5 Amount of conveyed powder vs discharge energy (Coil(01))

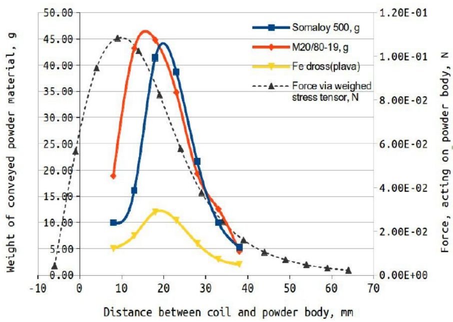


Figure 3.4.6 Influence of distance between powder and coil surfaces on effectiveness of conveying.

Investigating conveying process for, it was found, that there is a linear dependence between amount of conveyed material and a measured height where powder is conveyed to (Figure 3.4.7).

As a result, studies have demonstrated the possibility of experimental elevator for transportation of ferromagnetic powders. Different relationships between parameters influencing on conveying effectiveness have been defined. It was determined that the capture efficiency of powder depend on the distance between the coil and the surface of the powder. The dependence of the mass of material transferred from the particle size, and conveying height have been defined.

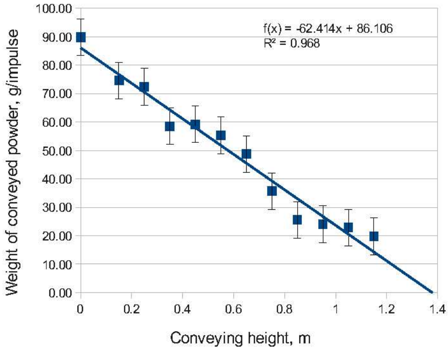


Figure 3.4.7 Weight of conveyed powder vs conveying height.

3.5 FIFTH CHAPTER. APPLICATIONS OF CONVEYING BY IMPULSE ELECTROMAGNETIC FIELD PHENOMENA.

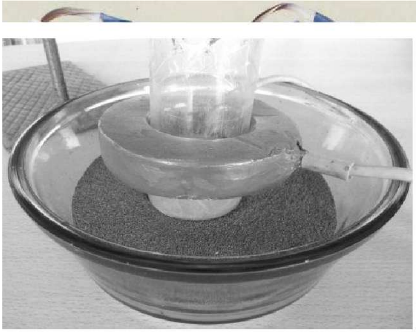


Figure 3.5.2 Semi-industrial conditions tests for conveying of iron powder M20/80-19 (max. height ~2 m)

On the basis of experimental works the following recommendations have been elaborated. For developing of an effective equipment for transportation of ferromagnetic powders by impulse electromagnetic field several important parameters have to be taken into account. A distance between coil and a surface of powder is a critical parameter for electromagnetic conveying. Laboratory test and modelling have shown that the distance between coil and a surface (h_1) of powder have to be more in range of $0.5h < h_1 < h$, where h – coil's height. Other parameters which have influence on productivity of electromagnetic conveyor are the following: discharge energy and distance of conveying.

An additional experimental work has been done in quasi-real conditions, when iron powder M20/80-19 has been conveyed from a larger reservoir (imitating a big bag filled with powder (Figure 3.5.1)) to the height up to 2 meters. Performed tests (Figure 3.5.2) have shown, on the one hand, a feasibility of electromagnetic conveyor, on the other hand, a need for further technical design study.

Conveying of compacted powder parts and solid iron bodies (nuts) has been tested [29]

Figure 3.5.3 Mixing by impulse electromagnetic field (iron powder in aqueous solution)

A tossing of ferromagnetic materials by impulse electromagnetic field has been performed in laboratory conditions. A similar approach can be used in bulk materials transport systems for collapsing of the vaults (vaults of conical hopper) [30]

An approach for mixing of different media has been developed [31], [32]. There are many possible applications, including power-powder, powder-liquid (Figure 3.5.3), liquid-liquid (by mean of ferromagnetic working medium), mixing of magnetic liquids [33].

Considering a powder metallurgy as a key industry dealing with ferromagnetic powders, electromagnetic conveying approach itself or in combinations with other processes can find its applications among powder metallurgy processes [34] [35] including an electromagnetic

injection of powder materials [36]
Extending parameters of laboratory-scale installation for industrial application is one of important criteria of laboratory system. The following table represents a prediction of potentially scalable components of electromagnetic conveyor EMC-05 designed at Riga Technical University Table 3.5.1.

Table 3.5.1: Scalability potential of electromagnetic conveyor EMC-05.

Parameter	**Laboratory-scale values**	**Perspective industrial applications**
Energy produced by generator of pulsed currents W, kJ	0.3-1.6	20
Peak current into coil I, kA	0.15-2	5
Operating voltage U, V	50-200	1000
Capacitance of capacitor bank, µF	30000-66000	1000-100000
Number of impulses, imp/min	10-60	Up to 100
Conveying speed, m/s	5-10	Up to 30
Maximum conveying height, m	0.5-2.0	3-6
Lifting power	0.5-2.0 kg/min	0.5-5 t/h

There are many advantages of suggested conveying approach. Amongst them:

- Transportation of materials in tube without physical contact with driving mechanism (screws, tape, trucks, etc.). In case of electromagnetic conveyor, a movement of material occurs due to the impact of electromagnetic fields on the material (ferromagnetic material).
- Ability to transport the material in different directions, tuning a speed boost by changing parameters of pulsed current source (voltage, capacitance of rechargeable battery of capacitors, use of different options for switching between panels).
- Ability to dose the material for filling, for example, in molds.
- Ability to transport the material in inert atmosphere (special gases), or in liquids.
- Transportation of material in liquids can be used for mixing purpose. Here, liquids are used for wetting and saturation of the materials transported by various substances and solvents (oils, anti-frictional liquids, anti-corrosion compounds).
- The possibility of combined transport of materials, for

example, pneumatic-electromagnetic method of transportation.

Along with advantages, there are some drawbacks which should be taken into account for future design implementations:

- Working with dangerous voltage sources. The risk of discharge currents for the personnel [37].
- A relatively short distance of transportation of the material.
- Possible interaction of pulsed magnetic fields with other equipment and materials [38].
- A need for special design of pulsed current sources and coils for long-term, continuous operation.
- Possible separation of the material into fractions during transport (segregation).
- The magnetization of conveyed materials [39], due to prolonged interaction with a pulsed magnetic field (magnetic saturation of the material).

4 CONCLUSIONS

- ✔ Studies have confirmed the possibility of ferromagnetic powders conveying by impulse electromagnetic field by mean of low-voltage equipment and experimental installation designed at Riga Technical University. This approach opens new opportunities for the transportation of iron and steel powders, as well as other ferromagnetic materials by impulse electromagnetic field.
- ✔ Modelling approach for further design of ferromagnetic materials conveying equipment by impulse electromagnetic field has been developed. It can be used for modelling of coils of different geometries and shapes, as well as for evaluating of magnetic interaction with different materials suitable for transportation by mean of suggested method.
- ✔ An experimental low-voltage equipment for study of the process of conveying by impulse electromagnetic field has been designed. Practical experiments have shown that such

type low-voltage equipment can be used for further experimental work with different iron powders and powder parts.

- ✔ Methods for experimental parameters measurements of conveying by impulse electromagnetic field have been developed.
- ✔ Recommendations on further applications of ferromagnetic materials conveying by impulse electromagnetic field have been formulated.
- ✔ Electromagnetic conveyor can be suggested as a solution for certain industrial applications, and especially for powder metallurgy and complementary processes.

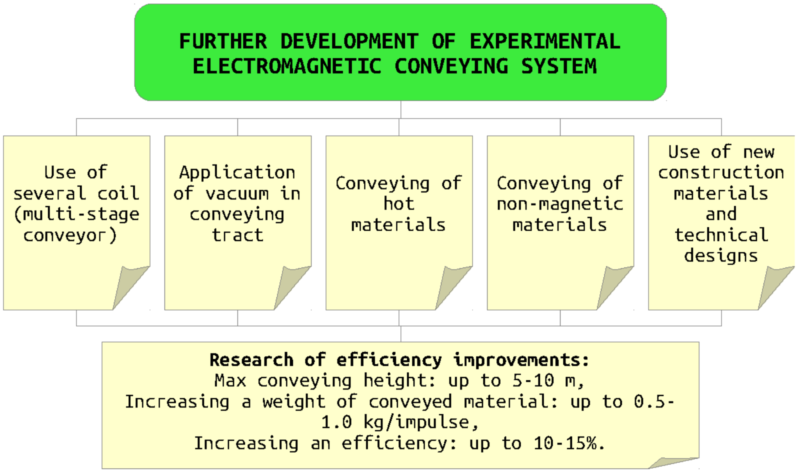
5 FURTHER WORK

Despite the fact that current research has confirmed a possibility and applicability of transportation of ferromagnetic powder materials by impulse electromagnetic field, there are many practical issues to be studied for implementation of electromagnetic conveying system into large-scale industrial plants.

Thanks to a long history of collaboration between Riga Technical University and the West Saxon University of Applied Sciences of Zwickau (Germany) [40] it will be possible to continue a research activity using a new equipment (Figure 5.1) [41], common knowledge and efforts for development and implementation of new conveying systems.

The following diagram overviews

some of further developments of electromagnetic conveying systems Figure 5.2.



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