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MAGNETIC CIRCUIT WITH LARGE BLOCKS FROM NdFeB MAGNETS FOR SUSPENDED MAGNETIC SEPARATORS

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ABSTRACT

The article provides the results acquired during the development of a magnetic circuit equipped with magnetic blocks assembled from NdFeB magnets with gradually increasing height. It presents the knowledge from the application of the new method of assembling these blocks and the achieved values of maximum magnetic induction in dependence on the distance from the surface of the blocks both for their different heights and for the different designs of the magnetic circuit in comparison with the values obtained for similar magnetic circuits with ferrite magnets.

KEYWORDS: magnetic circuits, magnetic separation, permanent magnets, NdFeB magnets, technological innovation

1. INTRODUCTION

Suspended magnetic separators above conveyor belts are intended for the capturing of undesirable ferrous objects randomly appearing in various transported materials – for example in the preparation of the raw materials for the production of tiles, in treating plastic or glass wastes, etc. These separators are used to increase the purity of the transported material and as a protection of the subsequent technological equipment from damage. In the case of a small amount of occasionally appearing ferrous objects, simple suspended magnets with a manually controlled cleaning mechanism are placed over the conveyor belts, with which it is necessary to remove the ferromagnetic share from the surface of the magnets periodically. On the other hand, wherever there is a great amount of this tramp iron in the transported material, belt suspended magnetic separators are used, whose belt moving above the surface of the magnets enables a continuous automatic removal of the captured magnetic share from the area of the magnetic field. In both of the mentioned cases, the magnetic field can be created by permanent magnets or an electromagnet.

In the case of suspended magnet, very important parameters are the magnitude and the direction of the magnetic field. The disadvantage of suspended separators with permanent magnets as compared with electromagnets is the low value of magnetic induction reached in the separation zone, because the magnetic force, which is proportional to the product of the magnetic induction of the outer magnetic field and its gradient and has the direction of the gradient (Svoboda and Fujita, 2003), is then too small particularly with the suspended separators with ferrite magnets, so far most used, and often does not allow the capture of ferromagnetic objects or elements. As is stated in the theory of magnetic separation of elements by a suspended magnet (Svoboda, 2004), in the case of a body at rest the vector of the minimum magnetic force necessary for the movement of an object is determined as the total of the vectors of the gravitational force and the force of the load of the material above the body. It is precisely this load by the material determined by the thickness of the layer and the type of material on the conveyor belt that significantly influences the strength of the magnetic force necessary for the capture of the body. Especially in the case of a thicker layer of material that is difficult to separate, like wet sand or clay, it is practically impossible for the separator with ferrite magnets to capture a body lying directly on the belt under a layer of such material. Moreover, the situation is further worsened by various cases appearing in practice when an unwanted ferromagnetic object is for instance "sandwiched" into a larger lump of wet clay. Unfortunately, simple measures allowing an increase in the effectiveness of the separation and lying in the reduction of the thickness of the layer of material on the belt or in bringing the magnets of the separator closer to the surface of the material transported have negative consequences – decreasing the thickness of the layer results in a lowering of the performance of the technological line, whereas bringing the magnets too close to the layer of the material can in the case of simple suspended separators without a discharging belt cause the objects that have already been captured to be pulled into the transported material.

Permanent magnets based on the rare earths (SmCo and especially NdFeB) are applied in various types of magnetic separators already for a longer time. Their use e.g. in roll and drum separators has enhanced the technical performance and economic viability of high-intensity magnetic separation (Arvidson and Henderson, 1997). They assert also in magnetic grids and rods and in suspended magnetic separators as well. In these cases are but mostly used assemblies from magnets of smaller dimensions, eventually from one layer of magnets only. The reason is the rapidly increasing big forces by which large magnets in process of their assembling interact with each other and affect surrounding ferromagnetic objects. Theoretical works concerning e.g. a computation of magnetic forces on small permeable particles in magnetic separators (Brauer et al., 2007) or a dynamic magnetic field computation in assembling process of hollow cylindrical permanent magnet assembly (Xie et al., 2007) are very interesting, nevertheless they are focused on rather different questions. For possibility of application on specific magnet assembly in suspended magnetic separator it would be need at first modify them by appropriate way.

In addition to the mentioned facts, the essential role in deciding on the next step was played also by the knowledge gained in the previous work when assembling circuits of magnetic filters for cleaning ceramic suspensions (Žežulka et al., 2005). Through the use of large magnetic blocks assembled from NdFeB magnets in the magnetic circuits of these filters, significantly higher values than in the case of the filters with ferrite magnets of magnetic induction were achieved in the separation zones, making it possible to reach a higher quality cleaning of the separated suspension. However, a necessary condition for the usage of these large magnetic blocks was always to determine a suitable technological procedure for their construction and their inserting into magnetic circuit, moreover, for their assembling into bigger units.

2. AIM OF THE WORK

The basic aim was to create a magnetic circuit with permanent magnets for suspended magnetic separators above conveyor belts that would reach high values of magnetic induction in the separation zone and thus allow a substantial increase in the probability of capturing the ferromagnetic objects of various materials on the conveyor belt without electrical energy consumption. For the testing of the feasibility of this plan, the decision was taken to assemble a trial magnetic circuit with the use of large blocks assembled from NdFeB magnets, making it possible to test the technology of assembling such a type of circuit itself and acquire the bases for the next step.

3. WORK PROCEDURE

The trial magnetic circuit, whose dimensional scheme is in Figure 1, was designed for the placement of six large magnetic blocks. In the figure, the circuit is depicted in the assembly position in which the magnet blocks are inserted into it. In the working position, the circuit is then turned 180° and suspended on lifting eye bolts. Just like with the above-mentioned magnetic circuits for magnetic filters, the basic construction element was also in this case a Compact magnetic plate comprised of six pieces of NdFeB magnets with dimensions of 0.05 x 0.05 x 0.03 m, magnetized as a whole. The outer dimensions of the plate including the perimeter frame of stainless steel were 0.16 x 0.107 m, with 0.03 m in height and a weight of 3.7 kg. In all of the plates, magnets of the N45 material were used; the magnetic parameters of this material from hysteresigraph test report are listed in Table 1. Each magnetic block was gradually assembled from one to three magnetic plates; after completion, this magnetic circuit thus contained eighteen plates with a total of 108 magnets of the mentioned dimensions.

The assembly and measurement of the trial magnetic circuit were conducted gradually in individual steps. In the first phase, only the internal side plates of non-magnetic stainless steel were

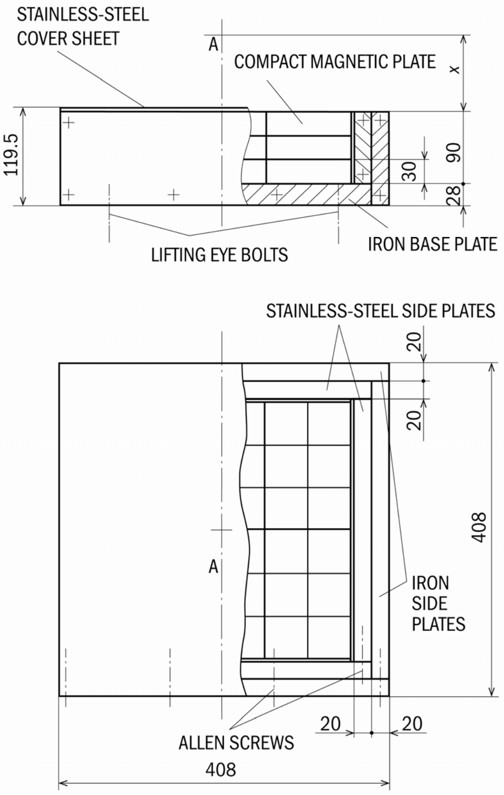

Fig. 1 Dimensional scheme of the magnetic circuit.

Table 1 Magnetic parameters of the material N45.

Material	N45
B_r [T]	1.354
H_{cb} [kA/m]	956
H_{cj} [kA/m]	992
$(BH)_{max}$ [kJ/m^3]	348
H_k [kA/m]	952
B_d [T]	0.678
H_d [kA/m]	514

attached to the base plate of common rolled construction steel (with the content of C being 0.17 %). Three of these side plates were welded to the base plate and each other; the fourth plate was removable and attached by means of Allen screws.

The circuit was subsequently equipped with magnetic blocks, first consisting of only of one compact magnetic plate, which were gradually inserted into the circuit. After insertion, the magnetic induction B_{max} was measured in dependence on the distance from the surface of the magnets x. For each set distance, the measurement determined the maximum magnetic induction reached in some point on a surface parallel to the surface of the magnets at a distance x above the surface of the magnets. Approximately from a distance of 80 mm above the surface of the magnets, this maximum magnetic induction was always measured in the axis of the magnetic circuit (indicated in Figure 1). When approaching from a distance of 80 mm towards the surface of the magnets, the point with maximum magnetic induction was further and further from this axis. The origin of this phenomenon was the non-homogenous distribution of the magnets in the given space, caused in particular by the perimeter non-magnetic stainless-steel frames of the individual magnetic plates, inaccuracies in the production of these frames and also clearances directly in the magnetic plates, filled with a sealing epoxy resin. In all of these cases, the problems are essentially air gaps, which negatively influence the measured results. It is a certain cost in exchange for the magnets not being glued in the course of assembly to one another with the minimum gaps but put into large blocks while using magnetic plates. When needed, however, this method unlike gluing allows an easy disassembly of the already assembled circuit, possibly the new magnetization of the individual plates and their new usage e.g. in another magnetic circuit.

After the magnetic induction $B_{max} = f(x)$ was measured, the plates were removed from the circuit and another plate was added to each of them. For the assembly of the plates into magnetic blocks, a new method was used (Žežulka and Straka, 2007), making it possible to control the speed of attraction of the magnets in their assembly in the direction perpendicular to the future common contact surface. This method lies in the gradual insertion of magnets or magnetic plates in the tube of the equipment, filled with a liquid (e.g. hydraulic oil), with the mutually adjacent surfaces of the magnets having the opposite polarity. The speed of their attraction is then possible to control by regulating the discharge of the liquid from the space between the magnets. Since the mutually approaching magnets attract one another the entire time, this method also allows the elimination of partial demagnetization, which can occur with magnets of material with low coercivity if they first mutually repel one another while they are approaching one another (Žežulka and Straka, 2008).

When assembling the magnetic blocks of the mentioned magnetic circuit, this method was still further simplified, because the speed of the attraction of the magnets also depends on the viscosity of the liquid and on the size of clearances in the tube of the equipment. Through the right selection of the oil used and restricting side sheets inserted along the inner walls of the tube, it is possible to reach a state when the magnets attract one another with increasing speed (which is however low also at the moment of attraction so that the magnets do not become damaged) but mainly without any discharge of the oil from the area between the magnets. Provided that the requirements for occupational safety when working with strong permanent magnets are observed, this method is safe, relatively fast, and the assembly of even large blocks of more pieces of compact magnetic plates can be managed by one worker.

Magnetic blocks, comprised of two plates, were again placed on the iron base plate of the circuit, and like in the previous case the dependence $B_{max} = f(x)$ was measured. Subsequently, the blocks were again withdrawn from the circuit and another compact magnetic plate was attached to each of them using the same method as described above. After the new insertion of these larger blocks (each of them weighed more than 11 kg) in the circuit and measurement like in the previous cases, they were again removed from the circuit.

In the next stage, outer perimeter plates (in Figure 1 and in the text below labeled as “iron side plates”), produced from the same construction steel as the base plate, were attached to the steel part of the circuit. Three outer plates were welded to the inner plates; the fourth was again removable and attached with screws.

The magnetic blocks, last removed from the circuit in the previous stage (each made up of three magnetic plates), were then gradually slid along the base plate of this circuit and the dependence $B = f(x)$ measured again. The completely assembled magnetic circuit without the stainless-steel cover sheet is depicted in Figure 2.

For the sake of completeness, it is possible to include also a photograph from the initial tests of the ability to capture ferromagnetic objects (Fig. 3), where the magnetic circuit described in the text above is already suspended in the working position. In the course of the tests, the ability to capture ferromagnetic objects from below layers of various materials (e.g. feldspar, sand, crushed stone) was being determined. Because of the significantly higher values of magnetic induction achieved in the separation zone in the case of a magnetic circuit with large blocks assembled from NdFeB magnets as compared to a circuit with ferrite magnets, also the magnetic force acting on the ferromagnetic object is substantially greater. It thus allows with greater probability the surmounting of not only gravitational force but also the forces acting on the object as a result of its being weighed down by the material above it. An example from the initial tests is that an M12-80 screw was withdrawn even from beneath a layer 80–90 mm high of crushed stone with a grain size of 8–16 mm from a distance of ca 200 mm.

The process of the attraction of steel screws from beneath the layer of crushed stone towards the surface of the magnets (at same conditions as in previous case) was recorded on video sequence by means of the digital camera. Selected photos from this recording (Figs. 4 to 7) picture stepwise individual phases of the attraction; the time period between first and last snapshot is about 0.5 s.

4. RESULTS AND DISCUSSION

All of the measured values of magnetic induction in dependence on the distance from the surface of the magnets for various heights of the magnetic blocks and designs of the magnetic circuit are provided in Table 2. For the sake of comparison, the table lists also the values of magnetic induction measured already before, reached with a similar magnetic circuit (but with a base plate without side plates) with large magnetic blocks of ferrite magnets with a height of 0.09 m and 0.15 m of material with the maximum energy product $(BH)_{max}$ being 29 kJ/m^3. The graphic illustration of all of the measured dependencies $B = f(x)$ is depicted in Figure 8.

It is clear from the measured values that in the case of a magnetic circuit with large NdFeB blocks comprised of three compact magnetic plates of a total height of 0.09 m, a three to more than four times higher value of magnetic induction was achieved in comparison with a similar magnetic circuit with ferrite blocks of a height of 0.15 m.

From the comparison of the two designs of magnetic circuits consisting of the same NdFeB blocks, it is evident that in the case of a magnetic circuit with stainless-steel and iron side plates the magnetic induction reached is higher in the range of distances x from zero to ca 140 mm but lower from ca 200 mm when compared with a circuit with only stainless-steel side plates. This fact allows the selection of the design of the circuit depending on its application purpose – in this case, this is a circuit for suspended magnetic separators, because in practical application of these suspended separators in industrial technological lines (for instance in the preparation of raw materials for the production of tiles, when treating plastic or glass wastes, etc.) the thickness of the layer on the conveyor belt is commonly in the range of 50–100 mm, possibly even more. The separator (its removable plate, possibly its discharging belt) should be set as close above the conveyor belt as possible, but the free passage of the material being separated must not be impeded and the captured ferromagnetic objects or elements must not be pulled into the transported material. The height of the setting of the actual magnetic circuit above the conveyor belt is thus in practice often in the range of ca 150–250 mm. For these cases of suspended magnetic separators, it is therefore more advantageous considering the higher magnetic induction attained (but also in terms of price) to select a magnetic circuit only with stainless-steel side plates. On the other hand, design of the magnetic circuit with the added iron side plates is more advantageous for lifting magnets, where the greatest attractive force possible is required right above the surface of the magnet.

5. CONCLUSION

1. When large blocks assembled from NdFeB magnets were used in the case of the presented type of magnetic circuit, the values of magnetic induction achieved in the separation zone were several times higher as compared to a similar circuit with ferrite magnets. This created the prerequisites for achieving substantially higher effectiveness of the magnetic separation of various materials as well as raw materials carried on a conveyor belt, due to the use of permanent magnets of course being without demands for electrical energy consumption and having relatively low costs.
2. As has already been verified with magnetic circuits for magnetic filters, the selected solution using large blocks assembled from NdFeB magnets makes it possible to achieve even higher values of magnetic induction and thus also of the parameters of the separation also with this type of circuit – for example through increasing the dimensions of the circuit, the height of the magnetic blocks (increasing the number of magnetic plates in a block) or using NdFeB magnets with higher energy product $(BH)_{max}$.
3. On the basis of the results so far, the successful verification of the technology of assembling a circuit and acquirement of further bases and knowledge, the decision has been taken to assemble a larger magnetic circuit for a functional model of a suspended magnetic separator allowing its insertion into a technological line in industrial operation for long-term technological tests. When this article manuscript was submitted to the editors, these tests were already being very

Table 2 Measured and comparative values of magnetic induction as a function of the distance from the surface of the magnets.

Distance from the surface of the magnets x [mm]	Magnetic induction B [T]					
	Magnetic circuit with ferrite blocks		Magnetic circuit with NdFeB blocks			
	with an iron base plate (a thickness of 15 mm)		with an iron base plate (a thickness of 28 mm) and stainless-steel side plates (a thickness of 20 mm)			with an iron base plate (a thickness of 28 mm), stainless-steel side plates (a thickness of 20 mm) and with iron side plates (a thickness of 20 mm)
	Height of the block 0.09 m	Height of the block 0.15 m	Height of the block 0.03 m (One plate)	Height of the block 0.06 m (Two plates)	Height of the block 0.09 m (Three plates)	Height of the block 0.09 m (Three plates)
0		0.151	0.4	0.46	0.535	0.585
4	0.108	0.138	0.334	0.39	0.451	0.501
10			0.263	0.344	0.401	0.446
20			0.205	0.293	0.341	0.386
30	0.073	0.104	0.17	0.256	0.308	0.349
40	0.065	0.091	0.15	0.23	0.28	0.312
50	0.058	0.082	0.133	0.208	0.259	0.285
60	0.052	0.073	0.121	0.192	0.237	0.26
70	0.047	0.065	0.11	0.175	0.219	0.238
80	0.044	0.056	0.102	0.162	0.201	0.217
100	0.035	0.046	0.087	0.139	0.171	0.182
120	0.03	0.036	0.073	0.117	0.145	0.151
140			0.062	0.099	0.124	0.125
160			0.051	0.084	0.103	0.103
180			0.045	0.07	0.087	0.087
200			0.038	0.06	0.075	0.072
250			0.025	0.04	0.052	0.048
300			0.017	0.028	0.037	0.034
350			0.013	0.021	0.027	0.024
400			0.01	0.016	0.021	0.017

successfully conducted. The results achieved will be published in a separate article.

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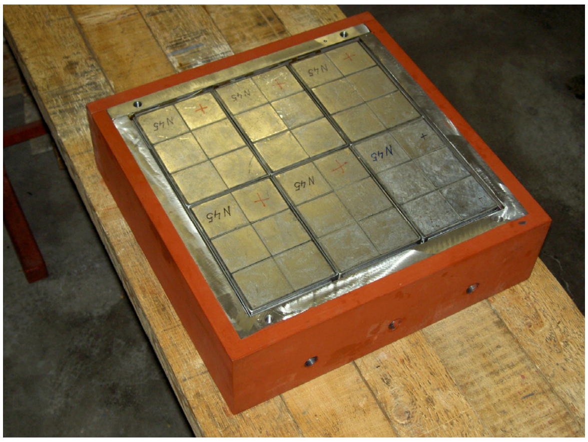

Fig. 2 Completely assembled magnetic circuit without the stainless-steel cover sheet.

Fig. 3 Initial tests.

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Figs. 4-7 Successive phases of the attraction of steel screws from beneath the layer 80-90 mm high of crushed stone from a distance ca 200 mm towards the surface of the suspended magnetic circuit (selected photos from video sequence).

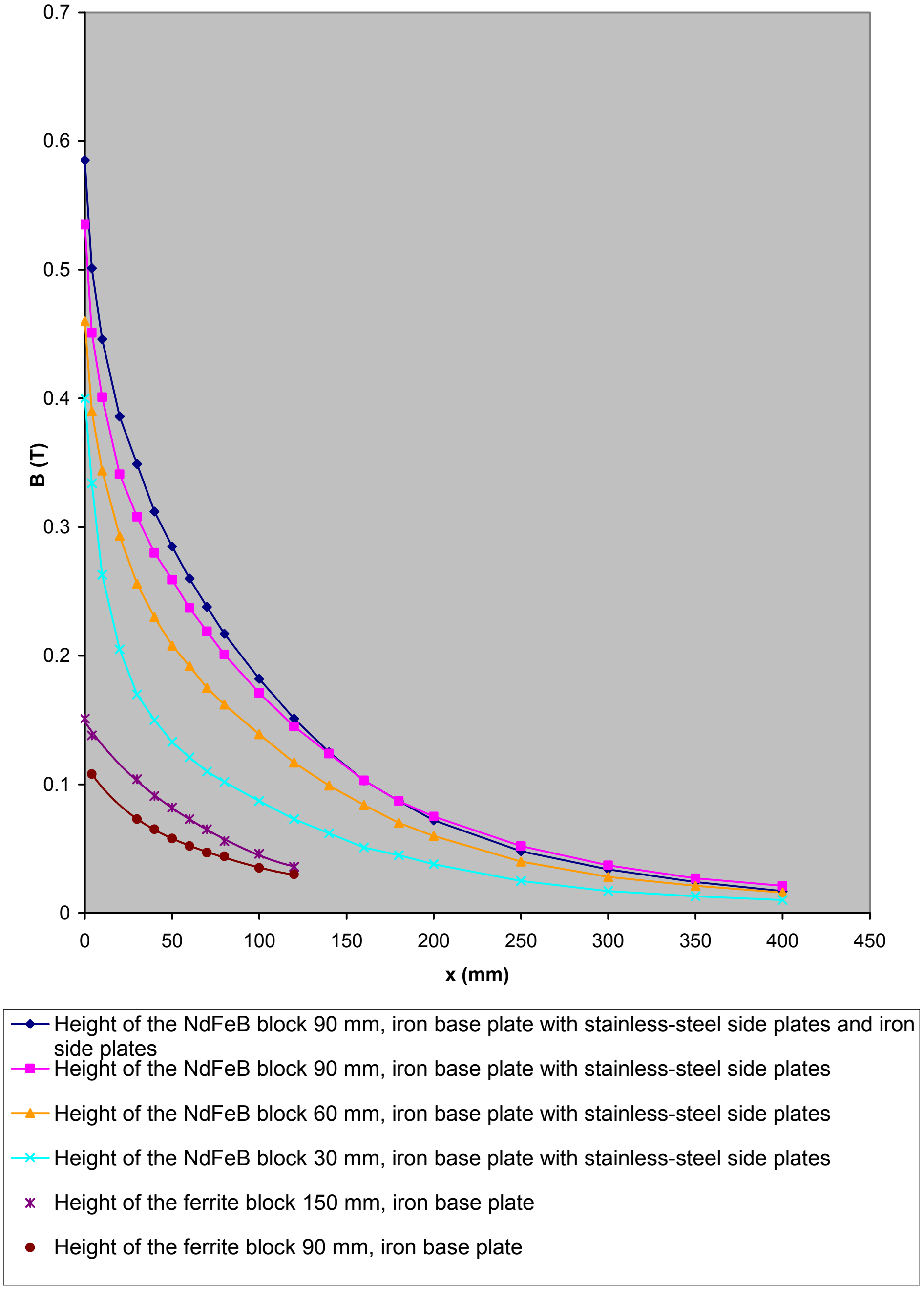

Fig. 8 Graphic representation of the dependences B=f(x).