GOUDSMIT MAGNETICS

Which factors influence the performance of magnetic separation systems, and why?

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Introduction

Right: A Goudsmit separation filter for removal of metallic particles from a liquid chocolate product flow.

Below: Current premises of Goudsmit Magnetics in Waalre – the Netherlands

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The magnetic separation systems from Goudsmit are used to capture metallic particles from liquid, gaseous or powder type of product flows to ensure a high quality end-product or minimum downtime of the production line equipment. Typically, by means of tube type magnet assemblies inserted into the product flow, a magnetic field is created in this flow that introduces magnetic forces on the particles to be captured. These cause the particles to be attracted towards the tubes and to be kept at the tube surface, despite the presence of other – flow related and opposing - forces, until these are removed in a cleaning step.

At Goudsmit, we frequently receive questions from customers on the performance of our separation systems. In particular, we receive questions like:

- How this performance is affected by the system parameters, e.g. by the strength of the magnets or by product flow properties such as viscosity?
- What our capabilities at Goudsmit are in quantifying this performance?

The aim of this document is to provide you with the answers to these questions.

For that purpose, we give you first a basic description of the factors that affect the separation performance of magnetic separation systems, and of how these factors affect this performance. After that, we present you an overview of the test and simulation methods with which Goudsmit quantifies this performance as a function of these factors. Additionally, at the end of this document, we answer directly various customer questions on separation performance, as encountered in dailiy practice and as not discussed yet in the remainder of this document.

This document may still not provide you an answer to your specific separation system performance related question. Please do not hesitate to contact us, if you have such an un-answered question.

What affects separation performance, and how?

Overview
The particle capture performance of a magnetic separation system is mostly affected by these factors:
- The strength of the magnets / magnetic material(s) used
- The configuration of the (tube) magnet assemblies used, their number and location
- The *amplitude* of the product flow velocity through the separation system
- The product flow velocity *distribution* in the separation system
- The resistance the particles meet from the product flow when migrating towards the magnet assemblies
- The size, shape and material of the particles to be captured

Strength of the magnets
The larger the strength of the magnetic material(s) used, the deeper the magnetic field penetrates in the product flow and the larger the magnetic field strength is close to the magnet assemblies. Consequently, the larger this strength, the further away particles will be captured by the magnetic field and drawn towards the magnet assemblies. Also, particles will experience a larger force close to the magnet and their tendency to stay at this surface will be larger. In other words, the larger the strength of the magnets, the better the separation performance.

Magnet assembly configuration, their number and location
The way the magnets are configured in the tubes also determines the separation performance as it affects how the magnetic field is distributed around the tube and in the product flow, and thereby with how much force the particles are attracted towards the tube surface and are held there. The volume around the tube should be covered with as large a region as possible with as high as possible magnetic field strength.

The more tubes are used in the separation system, the more volume in the product flow is covered with high magnetic field strength values and the better the separation performance will be. However, the more tubes, the more expensive the magnetic separation system and, additionally, the higher the pressure drop (gas an liquid product flows) and chance on flow blockage (powder flows). The number and location of the tubes also affect the product flow velocity *distribution* within the separation system and this, as also wil be discussed further on here, also affects the separaton performance.

Where the tubes are located in the separation system and, thereby, the way the magnetic fields around the tubes are oriënted with respect to each other can also affect the separation performance as this determines how the magnetic fields around the tubes interfere with each other, amplifying or cancelling each other at regions of the product flow.

Product flow velocity amplitude
A very important factor determining the separation performance of magnetic separation systems is the amplitude of the product flow velocity (or, equivalently, flow rate), as e.g. reflected by the *inlet* velocity (or flow rate). The simple rule here is that the higher this amplitude, the lower the separation performance. With a larger velocity the particles have a shorter residence time in the separation system, and this reduces the chance of the particles to be fully drawn towards the tubes.

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Product flow velocity distribution
The way the product flow velocity is distributed over the separation system also affects the separation performance as it affects the trajectories (location, velocity) of the particles to be separated. To name one extreme here, so called *dead zones* may be created in the system product flow volume, with close to zero velocity and low magnetic field strength, where particles may get stuck. The velocity distribution is affected by the geometry of the housing and the number, location and diameter of the tubes. The relation between these factors and separation performance is complex.

Flow resistance
When particles are migrating through the product flow towards the tubes, driven by the magnetic forces working on them, they encounter counteracting forces from the product flow. For liquids and gases, this resistance force is called the *drag force*, which is similar to the counteracting force a driving car experiences from the surrounding air. This drag force is highly dependent on the viscosity of the product flow. As a consequence, viscosity largely affects the separation performance as well. Particles are much more difficult to catch when, for example, they have to move through a viscous liquid chocolate flow than through a less viscous water flow. It is advised to consider adding a means of reducing the viscosity of a viscous product flow, when possible, to maximize the separation performance, for example by heating the product flow. This heating may reduce the strength of the magnets but this often is compensated for by the gain obtained through viscosity reduction.

Similarly for powder product flows, the metallic particles to be captured experience counteracting friction and collision forces from the powder particles when drawn towards the tubes through magnetic force, on top of drag forces from the gas (air) contained tin the powder product flow. With powders, many factors may affect the bonding of the powder particles, and thereby the obstruction of the particles to be separated and the separation performance. For example, sticky liquid bridges may be formed between powder particles in a humid environment. Or the very shape of powder particles may cause these to easily cling into each other and stick.

Powder product flows may even not flow at all through a separator. At Goudsmit we therefore always test for this before selling a separation system, when we suspect this could happen.

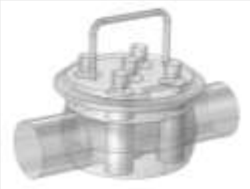
Particle properties
The separation performance will also depend on the size of the particles to be captured, with larger particles typically being more easily captured than smaller particles.

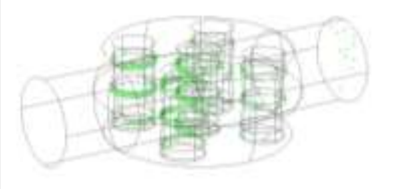
The way objects are affected by a surrounding magnetic field also depends on the shape of that object. Consequently, the shape of the particles to be captured will also affect the separation performance, with spherical particles being the most difficult ones to catch.

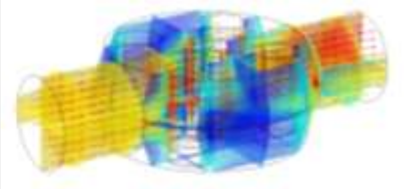
Finally, the material of the particles to be captured also affects the separation performance as each material is affected differently by a surrounding magnetic field. The influence of the magnetic field on a particle depends on its magnetic *permeability* or *susceptibility*. Values for these material properties are available in literature, and it is well known that common low carbon steel has a very much higher magnetic permeability than the most common stainless-steel types AISI316 and AISI304. Particles of low carbon steel are thereby typically relatively easy to catch while stainless steel particles are typically difficult to catch.

Example

To illustrate the effects of some of the factors affecting the performance of a separation system mentioned in the previous section, consider the separation performance values for a typical Goudsmit separation filter given in the table below:







Magnet material & grade	Remanence (T)	Particles captured (% of particles entering the filter)					
		AISI316, ø1mm	AISI304, ø1mm	LC steel, ø1mm	AISI316, ø0.1mm	AISI304, ø0.1mm	LC steel, ø0.1mm
Ferrite F47	0.46	38.1	65.2	100	8.0	22.6	100
Neodymium N35	1.17	50.2	96.6	100	12.3	68.0	100
Neodymium N52	1.42	51.7	98.9	100	13.3	77.1	100

FiEM computation results for the Goudsmit E0016970 filter where metallic particles are to be captured from a water product flow entering the filter at a velocity of 1 m/s. The particle capture performance is defined here as the percentage of particles captured on the tubes.

These results have been obtained with finite-element-method (FEM) calculations, where not only the magnetics but also the flow and the movement of the particles to be captured have been simulated. The particles to be captured were assumed to be spherical.

The results above clearly indicate that:

- Particle material affects the separation performance, with AISI316 particles less captured than AIS304 particles and both much less captured than low carbon (LC) steel particles, which are all captured here.
- Larger particles are more easily captured than smaller particles.
- The stronger the magnetic material, as expressed here in remanence value, the more particles are captured.

When using the same filter, Neodymium N35 magnetic material and – further - the same setup as above except for an inlet velocity that is reduced by a factor 2 (0.5m/s instead of 1m/s), one obtains the following results:

Magnet material & grade	Remanence B_r (T)	Particles captured (% of particles entering the filter)					
		AISI316, ø1mm	AISI304, ø1mm	v carbon steel, ø1ı	AISI316, ø0.1mm	AISI304, ø0.1mm	LC steel, ø0.1mm
Neodymium N35	1.17	70.1	100	100	21.4	92.9	100

Clearly, upon comparison with the table above, a reduction of product flow velocity enhances the separation performance.

Something to keep in mind

Although maybe clear from previous sections, one particular thing to keep in mind is that the performance of a separation system does not depend only on the characteristics of the magnets contained in this system. Magnetic system selection is not purely a matter of choosing the strongest possible magnets.

Magnetic separation system performance depends on metallic particle and product flow properties. That's why we often ask customers to specify metallic particle size and material, flow velocity or flow rate, viscosity in case of a liquid product flow, or certain powder characteristics in case of a powder product flow.

One should also realize that the number and location of the tubes inside a separation system affects both the magnetic field and flow velocity distribution in this system. As this interplay is complex, and as a result it can make magnet system selection complex as well. Next to knowledge about application system selection often requires the involvement of tests and/or simulations, to estimate the separation performance

Don't compare an apple with an orange

Due to the dependency of magnetic separation performance on other factors than pure magnetic strength, we cannot simply state that – when comparing two arbitrary separation systems for two arbitrary applications - one system performs better than the other simply because it has stronger magnets. This is illusttrated by the FEM results below obtained for a Goudsmit E0018608 filter and comparing these with those of the table on the previous page for the E0016970 filter:

Magnet material & grade	Remanence B_r (T)	Particles captured (% of particles entering the filter)					
		AISI316, ø1mm	AISI304, ø1mm	LC steel, ø1mm	AISI316, ø0.1mm	AISI304, ø0.1mm	LC steel, ø0.1mm
Neodymium N52	1.42	34.1	92.8	100	5.1	55.9	100

Particle capture performance for the Goudsmit E0018608 filter where particles are to captured from a water product flow entering the filter at a velocity of 1 m/s.

Here, despite having stronger (N52) magnets, the E0018608 filter performance is considerably worse than that of the E0016970 filter with weaker N35 magnets for the same application. For AISI316 particles, the E0018608 filter is even worse than the E0016970 filter with even much weaker F47 magnets for this application. This worse performance here can be attributed to a different flow velocity distribution and magnetic field distribution inside the filter, resulting from a different number, location, size and magnetic configuration of tube type magnet assemblies and different housing dimensions.

Performance testing & simulation

At Goudsmit, we use finite-element-method (FEM) modelling to determine the separation performance of *liquid or gaseous* product flow separation systems (which we call filters. FEM modelling is a well-established means of technical system or process modelling, in particular of those systems where the main process variables of interest, like for example magnetic field strength and fluid velocity, vary considerably over the space of interest.

Apart from estimating the particle capture performance, we also frequently use FEM modelling to simply compute the magnetic field within the filter or to estimate the pressure drop over a filter. Customers sometimes need this pressure drop information to determine the required (extra) pumping capacity in a production line, particularly for viscous product flows like e.g. liquid chocolate.

We use FEM modelling at Goudsmit for modelling liquid and gaseous product flows because of its relatively low cost and high accuracy. The accuracy of the FEM approach has proven itself already at many studies in its already considerably long history. It has also proven itself through various dedicated validation exercises at Goudsmit where model predictions have been compared to experimental test data.

For performance estimation of *powder* (solid-air) type of product flow magnetic separators, Goudsmit currently uses mostly (physical) testing, and not FEM modelling. The reason for that is that modelling of most of such flows has so far proven to be difficult, although Goudsmit has been investing in improving its capabilities in that respect (for example, in the application of the so-called Lattice-Boltzmann method for powder flow simulations, in cooperation with the company FlowMatter).

Testing is mostly done at the premises of the Goudsmit Test & Application Centre, although testing can also be performed at the customer site.

Despite all efforts to maximize the accuracy, testing and simulation still provides an at best approximative value of the separation performance, or of other system variables of interest. This is due to the testing and simulation conditions typically being at best an approximation of the real operating conditions of the magnetic separator under consideration. Performing a test or simulation under close to real operating conditions is most of the times difficult. Testing at the customer site may simply not be feasible or may not be desirable for the customer due to disturbing the regular production process, leading to unwanted costs. A specific problem that also may occur is inaccurate knowledge about the sizes of the particles entering the separator, leading to *assuming* a set or certain distribution of particle sizes.

Goudsmit documents the majority of its test and simulation results in a corresponding dedicated test or simulation report, which also contains a description of the conditions and assumptions under which the test and/or simulation results have obtained.

Tests and simulations can help us in, amongst others, (i) system selection, at the quotation phase, in (ii) identifying the best location of a system in a specific production line, and in (iii) new system development, in particular through the use of validated FEM models as these are relatively cheap and safe to apply. Additionally, tests and simulations can help you to answer performance questions raised during an auditing exercise at your company, thereby support in quality or legal questions.

Goudsmit Test & Application Centre

Since January 1st of 2022 Goudsmit has united its testing and simulation activities in its so-called *Test & Application Centre*.

What do we do?

• We answer technically complex questions on magnetic systems
• We determine magnetic system performances through testing on experimental setups and via modelling & simulation

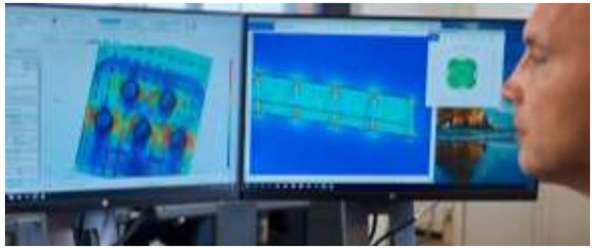
How do we do it?

• By maintaining a leading expert knowledge level on magnetism, magnetic materials, magnetic systems and on the testing, modelling and simulation of these systems - through training, courses and networking
• By translating this knowledge into high-quality, practical consults and performance assessments

Why do we do it?

• To increase the competitiveness and profitability of our customers by adding value to their products and by enhancing the quality of their decision-making processes

Our expertise lies not only in the field of separation but also in the fields of recycling, transportation of materials, production line automation, demagnetisation and magnet selection & optimization for sensing applications. Additionally, the Test & Application Centre has extensive experience in handling new applications that are outside these main fields of expertise.



Magnet inspection service

Apart from testing and simulating, as discussed in this paper, Goudsmit also provides the service of regular magnet inspections.

The main aim of these inspections is not to provide an estimate of the separation performance but to determine the integrity of the magnets in place. In particular their aim is to see whether the installed magnets have not lost too much on their strength compared to when these left the factory. Such losses in magnet strength may be due to e.g. temperature effects or the (accidental) nearby presence of a large demagnetizing field. Magnets that have been demagnetized too much are replaced by new ones. Also, other installation aspects are considered during the inspection.

Magnet inspection measurements are focused on measurement of magnetic field strengths c.q. magnetic flux densities at specific pre-specified locations in the considered magnetic system. Goudsmit provides a certificate after a magnet inspection, containing a summary of the main outcomes of the inspection.

Summary

The performance of a magnetic separation system is not only determined by the strength of the magnets used in this system. It is also affected by properties of the particles to be separated, product flow properties and the way the magnetic field and product flow velocity is distributed over the system by the magnet tube assemblies and housing. As a consequence, magnet system selection for a specific application is not simply a matter of choosing the system with the strongest magnets but can be much more complex.

Particular helpful tools in overcoming this complexity and, thereby, in supporting system selection are testing and simulation. Goudsmit has extensive experience with these tools and with their application for this and other purposes.

More information about the Goudsmit Test & Application Centre?

https://www.goudsmitmagnets.com/en/services/test-centre

More information about Magnet Inspections at Goudsmit?

https://www.goudsmitmagnets.com/services/magnet-inspections

More information about FEM calculations at Goudsmit?

https://www.goudsmitmagnets.com/solutions/service/calculation-and-simulation.html

Frequently asked questions

Is it possible to establish a relation that 8500 Gauss can remove 95% of metal pieces, 10000 Gauss can remove 98 % metal pieces, etc.?

Such a relation between Gauss value - or magnet strength expressed in other terms; see page on the right - and separation performance can indeed be determined for a specific separation system, product, inlet flow rate and particle properties. This can be done through testing or simulation.

In that case, we carry out multiple tests or simulations where at each such test or simulation we change the strength – and thereby the Gauss value referred to in the question above - of the magnets and determine the corresponding separation performance. Product, inlet flow rate and particle properties are held constant during these tests or simulations as these also affect the separation performance.

The resulting relation between Gauss value and separation performance is valid only for the considered separation system, product, inlet flow rate and particle properties. A relation determined for another system, product type, inlet flow rate or set of particle properties will be different because these other factors influence the separation performance as well (next to Gauss value). Hence, one generally cannot use a relation between Gauss value and separation performance determined for one system and application as an accurate description of this relation for another system and application. On the other hand, all derived relations between magnet strength and separation performance will be similar in the sense that an increase in magnet strength will cause an increase in separation performance.

Do you have a validation document that supports the observed relation between Gauss value and separation performance?

We do have such validation documents available but not for all of our systems and applications. This is because we do not derive for every one of our separation systems and for every application we encounter a relation between Gauss value and separation performance (as described above). An important reason for that is that magnetic separation systems typically already have been designed to have a large Gauss value (for instance, minimally 10000G on the tube surface at the poles) and thereby a high separation performance. As a result, deriving a relation between Gauss value and separation performance – as could be required during, for example, quotation - is often considered not to be necessary.

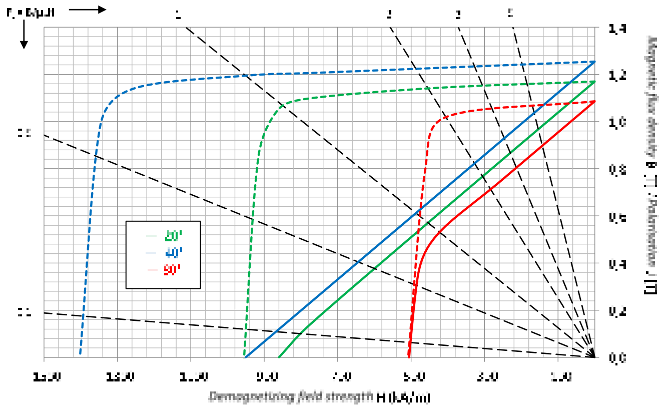
If we do derive a relation between Gauss value and separation performance through testing or simulation we indeed always report this.

Notes on Gauss values and magnet strength

In the field of magnetic separation, *the Gauss value* is typically used as a measure of the strength of the magnetic field present in the separation system and acting on the product flow and the particles to be captured present therein. Typically, this Gauss value is the value of the *magnetic flux density* on – and perpendicular to – the surface of a tube magnet near one of the (middle) poles, or is an average of multiple of these pole values at one or more of these tubes. This surface Gauss value can be measured relatively easy, which may explain its popularity. We note, however, that it is not a direct measure of the strength of the magnets used in the tube type magnet assemblies. Rather, it is an indirect measure, reflecting the combined strength of mulitple magnets contained in these tubes. Also, we note that a measurement on the tube surface does not provide an idea about the depth of the magnetic field in the product flow.

The strength of magnetic materials is actually expressed in terms of *remanence, coercitivity* - which is a measure of the material against demagnetization – and/or *maximum energy product* - which magnitude is reflected in the *grade* number of the considered magnetic material. These are all parameters contained in the so called *demagnetization curve* (which is part of the so called *BH*- or *hysterysis* curve) corresponding to the considered magnetic material. This curve describes each possible magnetic operating point at each location in a magnetic material. See below for the demagnetization curves for Goudsmit Neodymium N35 magnetic material for several temperatures (solid lines), and corresponding properties like remanence (B_r), coercitivity (H_{cB}) and maximum energy product ($(BH)_{max}$). A full discussion of this subject is outside the scope of this document, however.

Demagnetization curve N35



Magnetic properties @20°C			
B_r	min	1.17	T
H_{cB}	min	860	kA/m
H_{cJ}	min	955	kA/m
$(BH)_{max}$	min	259	kJ/m^3
$\alpha(B_r)$	min typ	-0.12	%/°C
$\beta(H_{cJ})$	min typ	-0.78	%/°C
T_{max}		80	°C
μ_r	typ	1.05	-

Gauss value refers to the usage of *Gauss (G)* as a unit for magnetic flux density. However, this unit is – although still being extensively used n practice - not the formally correct unit for this quantity. The correct (SI = Système Internationale) unit is *Tesla (T),* with 1T = 10000G.

What is the minimum Gauss value a magnetic separation system should have?

This differs for each application and magnetic separation system. It also depends on what you, as a customer, consider as a minimum acceptable separation performance: what percentage of the considered particles should be captured for you to be considered as an acceptable separation performance?

If we have agreed with you upon this minimum acceptable performance, we can determine for you the minimum Gauss value that corresponds to this performance, i.e. through testing or simulation. We then carry out multiple tests or simulations where at each such test or simulation we change the Gauss value and determine the corresponding separation performance. We obtain then a relation as described in the first question discussed above in this section on frequently asked questions. Product, inlet flow rate and particle properties are held constant during the tests or simulations as these also affect the separation performance.

The resulting relation between Gauss value and separation performance is valid only for the considered separation system, product, inlet flow rate and particle properties. A relation determined for another system, product flow type, inlet flow rate or set of particle properties will generally be different because these other factors influence the separation performance as well. Hence, one generally cannot use a relation determined for one system and application as an accurate description of this relation for another system and application. As a consequence, a minimum Gauss value derived for one system and application is also generally not valid for another system or application.

Does viscosity of the product flow influence the separation performance?

Yes, for separation filters an increase in viscosity makes the migration of particles to be captured through the product flow towards the magnet tubes more difficult as it increases the drag force on these particles. This drag force can be seen as a friction force acting by the product on the particle, in particular when moving, it is similar to the drag force introduced on cars in motion by surrounding air.

In a similar way, stickiness of powder type of product flows reduces the separation performance.

Heating of the product flow may decrease the viscosity more than the magnetic strength and, thereby, improve the particle capture performance considerably. Some of our magnetic separation systems provide an extra heating capability to reduce the product flow viscosity, for example for liquid chocolate flow applications.

GOUDSMIT MAGNETICS

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