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CORSO DI LAUREA SPECIALISTICA IN

INGEGNERIA PER L'AMBIENTE E IL TERRITORIO

TESI DI LAUREA IN
VALORIZZAZIONE DELLE RISORSE PRIMARIE E SECONDARIE

OTTIMIZZAZIONE DI UN PROCESSO DI SEPARAZIONE MAGNETO-GRAVIMETRICA IN FRAZIONI MULTIPLE

OPTIMIZATION OF A PROCESS FOR THE MAGNETIC DENSITY SEPARATION INTO MULTIPLE FRACTIONS

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Abstract

Principi sulla separazione in fluidi magnetici

La separazione dei materiali in base alla densità è una tecnica universalmente riconosciuta: risulta essere uno dei più antichi metodi di lavorazione dei materiali.

Immergendo un oggetto di densità ρ in un fluido con densità ρ_f, esso galleggerà se $\rho < \rho_f$ o affonderà se $\rho > \rho_f$. Con questa semplice strategia è possibile separare materiali di diversa densità.

Il principio alla base della separazione magneto-gravimetrica prevede l'utilizzo di un fluido magnetico quale mezzo ideale di separazione. Questo fluido, costituito da una sospensione di particelle nanometriche di magnetite in acqua, ha una densità ρ_f relativamente bassa. In presenza di un campo magnetico, la sua densità varia per il contributo della forza magnetica, il cui effetto si somma a quello della forza di gravità. Pertanto, per un fluido di magnetizzazione M, soggetto ad un gradiente magnetico ∇B, si ha:

$$\rho_a = \rho_f + \frac{M\nabla B}{g} \qquad \text{densità apparente del fluido magnetico}$$

Per un fluido magnetico immerso in un campo la cui induzione magnetica varia esponenzialmente con l'asse z, la densità apparente segue la legge:

$$\rho_a(z) = \rho_f + \frac{M\nabla_z B}{g} = \rho_f + \frac{2\pi M B_0}{gw} e^{-2\pi z/w}$$

La densità del fluido sarà cioè maggiore negli strati più vicini al magnete, minore nelle zone più lontane. Pertanto un materiale immerso nel fluido tende a stazionare ad una determinata altezza (distanza dal magnete), in corrispondenza della quale la sua densità è uguale a quella del fluido.

Il Prof. Rem dell'Università di Delft (Paesi Bassi) ha progettato e brevettato un magnete che permette di ottenere un fluido magnetico con queste caratteristiche.

La separazione magneto-gravimetrica

Per poter sfruttare le proprietà dei fluidi ferromagnetici è stato messo a punto un separatore magneto-gravimetrico, grazie al quale è possibile separare diversi materiali in un solo processo. Il separatore è costituito da un canale vibrante in ottone posto sopra ad un magnete. Il fluido magnetico e i materiali da trattare sono inseriti all'interno del canale, dove avviene la separazione. I materiali vengono separati in base alla loro densità: ciascun materiale raggiunge una quota definita, punto di equilibrio tra la sua densità e quella del fluido.

La prima configurazione del separatore è stata usata per la separazione di diamanti da altri minerali. I risultati ottenuti sono stati incoraggianti.

Si è allora deciso di proseguire la sperimentazione, migliorando il separatore in alcuni punti e procedendo all'acquisto di nuove pompe.

Più in dettaglio, il processo di separazione può essere così riassunto:

- Il fluido magnetico viene fatto passare attraverso un laminatore, per evitare l'innesco di moti turbolenti che pregiudichino il processo. All'uscita del laminatore il fluido si mescola con i materiali destinati alla separazione (convogliati attraverso un ingresso preferenziale). L'insieme giunge quindi nell'area di separazione, soggetta al campo magnetico.
- Nell'area compresa tra il laminatore e gli scomparti di uscita avviene l'intero processo di separazione. In questa area il fluido magnetico è soggetto ad un campo magnetico non uniforme, pertanto il fluido ha una densità variabile a seconda della distanza dalla superficie del magnete. Ogni materiale immerso in questo fluido stazionerà ad un'altezza caratteristica, in funzione della propria densità.
- Un opportuno dispositivo sottopone il canale a vibrazione durante il processo per evitare che i materiali si accumulino sul fondo o sulle pareti laterali del canale stesso.
- Alla fine del campo magnetico i materiali sono convogliati in cinque diversi scomparti (ognuno dei quali è costituito da tre lastre orizzontali che formano due settori di 10 mm di altezza). All'uscita di ciascun scomparto il fluido e il materiale vengono pompati verso un setaccio.
- Ogni setaccio provvede ad isolare la frazione di materiale dal fluido magnetico. Il materiale viene lavato e recuperato, mentre il fluido magnetico viene reintegrato nel processo mediante una pompa di ricircolo.

Esperimenti

Sono stati condotti diversi esperimenti al fine di valutare la bontà del processo di separazione e l'influenza di alcuni parametri sul processo stesso.

Nel primo esperimento sono state utilizzati tre tipi di plastica, le cui densità sono state misurate sperimentalmente con un picnometro a gas:

- PET: $\rho_{PET} = 1351$ kg/m^3
- PMMA: $\rho_{PMMA} = 1215$ kg/m^3
- ABS: $\rho_{ABS} = 1053$ kg/m^3

Per la separazione di questi materiali si è reso pertanto necessario un fluido magnetico che, sottoposto a un campo magnetico non omogeneo, variasse la propria densità all'interno dell'intervallo di valori 1050 - 1350 kg/m^3. A tal fine, il fluido magnetico puro ($M = 18000$ A/m, $\rho_f = 1156$ kg/m^3) è stato diluito con 29 parti di acqua per raggiungere un intervallo di densità compatibile con i materiali.

Successivamente è stata valutata l'altezza di galleggiamento di ciascun materiale, grazie ad un modello teorico sulla distribuzione della densità nel fluido e ad alcune prove pratiche. Ne è risultato che il PET affonda, di conseguenza dovrebbe essere raccolto nel primo scomparto, quello cioè più vicino alla superficie del magnete. L'ABS dovrebbe invece galleggiare sulla superficie del fluido, per essere raccolto nel quinto scomparto, cioè quello più lontano dal magnete. Infine il PMMA dovrebbe flottare ad un'altezza intermedia, per essere recuperato nel secondo e nel terzo scomparto.

Sono stati svolti numerosi test per determinare i parametri ottimali ai fini del processo. La miglior separazione è stata ottenuta con i seguenti accorgimenti:

- I materiali sono stati precedentemente "bagnati" con un getto di vapore acqueo. In questo modo è stata scongiurata la formazione di bolle d'aria sulla superficie del campione, con inevitabile alterazione (diminuzione) della densità del materiale.
- La potenza delle pompe è stata regolata al 20% della loro capacità (pompe sovradimensionate rispetto alle dimensioni del canale di separazione).
- Un alimentatore vibrante ha provveduto all'alimentazione dei materiali.
- Sono stati processati campioni con peso complessivo non superiore a 30 g per evitare problemi di intasamento delle connessioni tra le pompe e i tubi.
- Il separatore è stato posto 4 mm al di sopra del magnete.

Il campione, costituito da PET, PMMA ed ABS, è stato inserito all'interno del sistema. Dopo alcuni secondi la separazione delle tre plastiche era già visibile. Tutto il PET è stato recuperato all'interno del primo setaccio (scomparto più basso, vicino alla superficie del magnete). Anche la separazione dell'ABS è avvenuta in modo ottimale, visto che tutto il materiale è stato raccolto nell'ultimo scomparto (il più lontano dal magnete), destinato alle frazioni più leggere. Il PMMA, la cui densità è intermedia, è stato raccolto in maggior parte nel terzo scomparto; la sua separazione non è stata ottimale perché piccole frazioni sono state raccolte sia nel secondo che nel quarto scomparto. Probabilmente questa frazione intermedia è maggiormente soggetta a fenomeni di perturbazione dovuti alla turbolenza nel flusso e/o all'interazione con i diversi materiali.

Altri test sono stati condotti utilizzando dei rifiuti da apparecchiature elettriche ed elettroniche (RAEE) forniti dall'azienda Axion Recycling Ltd, un insieme finemente macinato di plastiche (prevalentemente PVC), pietre, vetro e fili elettrici di rame.

L'obiettivo era quello di ottenere una frazione di rame più pura possibile.

L'elevata densità del rame lasciava supporre che questo venisse raccolto nella parte inferiore del separatore, e che tutti gli altri materiali, più leggeri, fossero destinati agli scomparti superiori.

Nonostante alcuni problemi di intasamento dei setacci, causati dalla forma e dalle dimensioni dei materiali trattati, i risultati ottenuti sono stati soddisfacenti. Il rame è stato recuperato nel primo setaccio, senza alcuna contaminazione da parte degli altri materiali, che si sono invece suddivisi in frazioni più leggere.

Conclusioni

La tecnologia di separazione magneto-gravimetrica è innovativa in quanto permette di separare materiali diversi in un solo passaggio. Si possono separare con risultati molto buoni sia materiali caratterizzati da densità simili a quella dell'acqua - plastica, sia materiali con densità decisamente superiori, come il rame, l'oro ed il platino.

Il processo potrà essere esteso a materiali di dimensioni maggiori utilizzando un canale più ampio.

Software di ausilio potranno invece essere impiegati per uno studio più approfondito del processo di separazione (simulazione del flusso, analisi dell'interazione tra i diversi materiali all'interno dell'area di separazione).

Le applicazioni di questa tecnologia ricoprono sia il campo dei rifiuti, dove il recupero dei materiali risulta economicamente vantaggioso ai fini industriali (si pensi ai metalli, che possono essere venduti alle filiere di riferimento), che quello dell'estrazione mineraria, dove si possono separare minerali e/o metalli preziosi da altri minerali o metalli.

Introduction

This project has been carried out at the Delft University of Technology, Section of Materials & Environment - Recycling Technology Laboratory.

In the first chapter the theory of the magnetic separation has been presented. The sink and float technique of gravity separation relies on selective levitation and sinking of materials based on their relative densities and that of the separating medium. In this study the application of magnetic fluids as a heavy medium has been investigated. The concept of separation of non-magnetic particles suspended in a magnetic fluid is based on the generalized Archimedes law whereby, in addition to the conventional force of gravity acting on the fluid, also a magnetically induced force acts on the fluids. This additional magnetic pull creates a magnetically induced buoyancy force on a particle immersed in the fluid. This buoyancy force can be controlled in a wide range of values and materials as dense as 20000 kg/m^3 or higher can float in such a fluid.

In the second chapter some former tests with this technology have been shown and the re-building of the magnetic density separator has been described. A separator has been designed in order to separate multiple density fractions at once. The main part of the separator is a brass vibrating gutter. Fluid and non-ferrous materials are led into the gutter, straight into the magnetic field where the separation begins. At the end of the magnetic field the different density fractions are pumped towards a sieve. Here the materials are collected and the fluid is recovered and circulated.

In the third chapter some experiments have been performed and results have been shown. The tests have been carried out with different samples. Plastics as well as material derived from WEEE have been used. The separation of the plastics shows the whole potential of this process: they are recovered in different fractions on the grounds of their density. The separation of a sample coming from mixed materials derived from WEEE has been done in collaboration with Axion Recycling Ltd. A pure fraction of copper has been obtained.

In the last chapter the results have been discussed and new ideas for future developments have been given.

Chapter 1

Theory of magnetic separation

1.1 Magnetism and innovation in magnetic separation

Magnetic phenomena have been known and exploited for many centuries. The earliest experiences with magnetism involved magnetite, the only material that occurs naturally in a magnetic state. Thales of Miletus stated that the magnetic interaction between lodestone, or magnetite, and iron was known for at least as long ago as 600 B.C. That magnetite can induce iron to acquire attractive powers, or to become magnetic, was mentioned by Socrates. Permanent and induced magnetism, therefore, represents one of man's earliest scientific discoveries.

Practical significance of magnetic attraction as a precursory form of magnetic separation was recognized in 1792, when W. Fullarton obtained an English patent for separating iron ore by magnetic attraction. Since that time the science and engineering of magnetism and of magnetic separation have advanced rapidly and a large number of patents have been issued. While separation of inherently magnetic constituents was a natural early application of magnetism, Wetherill's separator, devised in 1895, was an innovation of significant proportions. It demonstrated that it was possible to separate two components, both of which were commonly considered to be non-magnetic. In the ensuing time various types of disk, drum and roll dry magnetic separators were developed although the spectrum of minerals treatable by these machines was limited to rather coarse and moderately strongly magnetic materials. Since the end of the nineteenth century there has been a steady expansion of both the equipment available and the range of ores to which magnetic separation is applicable.

The development of permanent magnetic materials and improvement in their magnetic properties has been main drivers of innovation in magnetic separation. Figure 1.1 illustrates the history of improvement of the maximum energy product max of permanent magnets. Three innovation milestones can be identified in the graph. At the end of the nineteenth century very feeble steel based magnets were employed, while in the 1940s permanent magnets that were able to compete with electromagnets, were developed. Probably the most important innovation step was made in the late seventies of the last century when rare-earth magnets became available. These magnets allowed new solutions for challenges that were not possible or feasible with electromagnets.

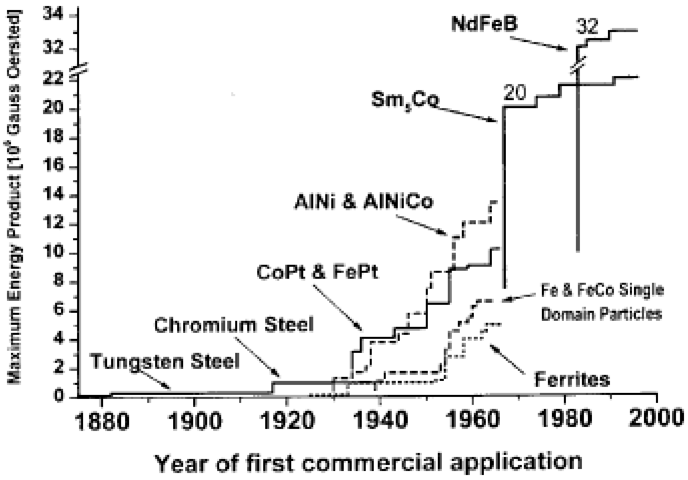


Figure 1.1 - Development of permanent magnet materials.

Another significant driver of innovation in magnetic separation was the introduction of ferromagnetic bodies (such as balls, grooved plates or mesh) into the magnetic field of a separator. In 1937 Frantz developed a magnetic separator consisting of an iron-bound solenoid packed with ferromagnetic steel ribbons and this proved to be an important milestone in the development of the present high-intensity and high-gradient magnetic separators. This innovation extended the range of applicability of magnetic separation to many weakly magnetic and even to diamagnetic minerals of the micrometer size.

Although the significance of the discovery of superconductivity has been equated with the invention of the wheel, its importance for magnetic separation does not seem to represent a major breakthrough. The need for magnetic induction greater than 2 Tesla has never been convincingly demonstrated in matrix separators and the main advantage of superconducting magnets is, therefore, the reduced energy consumption and the possibility of generating a high magnetic force in large volumes, even without using matrices.

The concentration of various ferrous and non-ferrous minerals has been an important application of magnetic separation, as has the removal of low concentrations of magnetizable impurities from industrial minerals. In recent years, as a result of numerous economic, environmental and social challenges, the recycling of metals from industrial wastes and the concentration or removal of biological objects in medicine and biosciences have become important areas of application of magnetic technology. Recent research and development of eddy-current separators, magnetic fluids and magnetic carriers illustrate the enormous effort that has been expended over the last twenty years in order to convert a wealth of novel ideas into workable techniques and introduce them into material manipulation operations.

1.2 Fundamental quantities of magnetism and their units

In physics, a magnetic field is a vector field that permeates space and which can exert a magnetic force on moving electric charges and on magnetic dipoles (such as permanent magnets). When placed in a magnetic field, magnetic dipoles tend to align their axes to be parallel with the magnetic field. In addition, a changing magnetic field can induce an electric field. Magnetic fields surround and are created by electric currents, magnetic dipoles, and changing electric fields. Magnetic fields also have their own energy, with an energy density proportional to the square of the field intensity.

1.2.1 Magnetic field and magnetization

When a magnetic field is described, two different quantities, namely magnetic field strength H [A/m] and magnetic flux density (or magnetic induction) B [T], are employed.

H and B are both vector quantities having direction as well as magnitude. In vacuum B and H are not independent and are related by the equation:

$$\vec{B} = \mu_0 \vec{H} \qquad (1.1)$$

where $\mu_0 = 4\pi \cdot 10^{-7}\ H/m$ is the magnetic permeability of vacuum.

In a magnetic material of magnetization M [A/m], the total magnetic induction becomes:

$$\vec{B} = \mu_0 \left(\vec{H} + \vec{M} \right) \qquad (1.2)$$

Magnetization is defined as the total magnetic moment μ_M [Am^2] of dipole per unit volume V [m^3], i.e. $M = \mu_M / V$.

In SI *B* is given by:

$$\vec{B} = \mu_0 \vec{H} + J \qquad (1.3)$$

where *J* [T] is the magnetic polarization.

J and *M* are related by the following equation:

$$\vec{J} = \mu_0 \vec{M} \qquad (1.4)$$

The magnetic induction thus includes contributions from the magnetization *M*, which is defined as the magnetic dipole moment of a body per unit volume, or polarization *J* defined by eq. (1.4).

1.2.2 Magnetic susceptibility and permeability

The magnetization of a material depends on the magnetic field acting on it. For many materials, *M* is proportional to *H*:

$$\vec{M} = k\vec{H} \qquad (1.5)$$

where *k* is the volume magnetic susceptibility, a property of the material. Since *M* and *H* have the same dimensions *k* is dimensionless.

We can combine eq. (1.5) with eq. (1.2) to get:

$$\vec{B} = \mu_0 (1+k)\vec{H} = \mu_0 \mu_r \vec{H} = \mu \vec{H} \qquad (1.6)$$

where

$$\mu_r = 1 + k \quad \text{and} \quad \mu = \mu_0 (1+k) \qquad (1.7)$$

The quantity μ_r is called relative magnetic permeability and is dimensionless, while μ is called magnetic permeability and has a unit of H/m.

While eq. (1.2) is general, eqs. (1.6) and (1.7) are based on assumption that the material is both isotropic and linear. In other words, that *M* is proportional to *H* and in the same direction. This assumption is never completely true for ferromagnetic materials.

Either μ_r or *k* may be used to characterize a material. Volume magnetic susceptibility *k* ranges from values close to 0, both positive and negative, to positive values greater than 1, for different materials. For materials that have very small susceptibility, it is much convenient to use *k* than μ_r.

Magnetic susceptibility can also be expressed with respect to the unit mass of material density ρ, and then

$$\chi = \frac{k}{\rho} \qquad (1.8)$$

where χ [m^3/kg] is the mass, or specific, magnetic susceptibility. Since a sample mass m is usually better known than its volume, mass magnetic susceptibility is very commonly employed. For the same reason the mass magnetization σ [Am^2/kg] rather than magnetization M is often used to characterize materials.
The mass magnetization is defined as:

$$\sigma = \frac{\mu_M}{m} \quad \text{thus} \quad M = \rho\sigma \qquad (1.9)$$

1.3 Magnetic properties of materials

It has been stated at the outset that all materials display certain magnetic properties, regardless of their composition and state. According to their magnetic properties, materials can be divided into five basic groups: diamagnetic, paramagnetic, ferromagnetic, antiferromagnetic and ferrimagnetic. The last three groups have generally higher magnetic susceptibilities than the other groups and are frequently termed ”ferromagnetic” sensu lato (s.l.). This broad definition must be distinguished from one of its subdivisions, ferromagnetic sensu stricto (s.s.) as discussed below. The alignment of magnetic moments in each type of material is shown in Fig. 1.2.

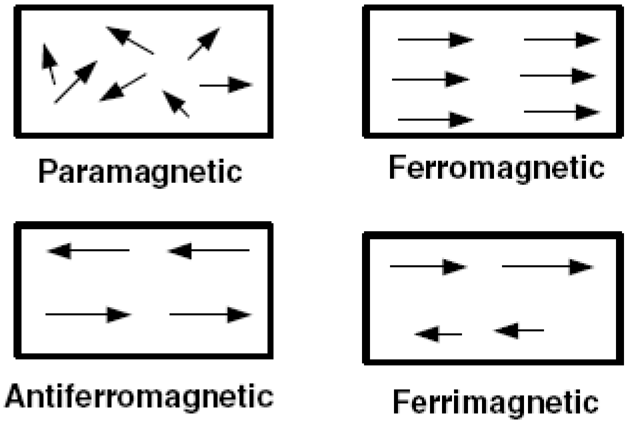


Figure 1.2 - Schematic diagram of the alignment of magnetic moments.

Diamagnetism has its origin in the modification of the electron orbit magnetic moment by an external magnetic field. The currents thus induced give rise to an extra magnetic moment. However, according to Lenz's law, the resulting magnetic moment is in the opposite direction to the field that has induced the current. Therefore, approaching a source of the magnetic field, a diamagnetic material is repelled from it. This effect is present in all materials, independently of temperature.

In paramagnetic materials the magnetic atoms or ions have permanent intrinsic magnetic moments and occur in low concentrations. Susceptibility arises from the competition between the aligning effect of the applied magnetic field and the randomizing effect of thermal vibrations. In zero applied magnetic field, the moments point in random directions. When a field is applied, a small magnetization develops, but the magnetic susceptibility is very small and is inversely proportional to the absolute temperature.

In ferromagnetic materials (s.s.) interaction between neighbouring atoms is strong so that the magnetic moments of all atoms are aligned parallel to each other against the randomizing force of thermal motion. The strong internal fields, which align the spins, are called molecular or Weiss fields. These fields are the result of a quantum mechanical process called exchange interaction. Weiss assumed that the molecular field is very large, its magnitude independent of external magnetic field, and its direction not fixed, but always parallel to the magnetization. The Weiss hypothesis predicts that a material can be spontaneously magnetized even in the absence of an applied magnetic field at temperatures below the Curie temperature, at which the thermal agitation overcomes the molecular field. This tendency aids the external field in producing saturation, i.e. complete alignment. There is an apparent contradiction between theory, which explains that magnetic materials are fully magnetized even in the absence of an external field, and practice, which generally shows that such materials exhibit no magnetization or magnetization much smaller than saturation. In fact, theory is correct at a microscopic level, but at a macroscopic scale the ferromagnetic body is subdivided into Weiss domains, each of which is spontaneously magnetized to saturation, but not in the same direction, by virtue of a strong exchange magnetic field. Inside a domain the magnetization is at a maximum (saturation), but as all domains compensate each other, on macroscale the mean magnetization is nil.

The value of the saturation magnetization varies with temperature, decreasing from a maximum value at T=0 K, becoming zero at the Curie temperature T_c. Above T_c, the behaviour is similar to that of a paramagnetic material, with the magnetization being proportional to the field and the susceptibility decreasing with increasing temperature.

In contrast to diamagnetic and paramagnetic materials, magnetization of ferromagnetic materials (s.l.) depends not only on the field strength, but also on the shape and the magnetic history of the sample. For instance, a ferromagnetic material can remain magnetized after removal of the external field.

Antiferromagnetic materials were originally thought of as a class of anomalous paramagnets, since they have small positive susceptibilities of similar magnitude to many materials of the latter class. However, their magnetic susceptibility does not increase steadily as the temperature decreases all the way to absolute zero.

In a ferrimagnetic material magnetic moments are ordered regularly in an antiparallel sense, but the sum of the moments pointing in one direction exceeds those pointing in the opposite direction.

The magnetic properties of ferromagnets and ferrimagnets are generally similar: both exhibit saturation and their magnetization is much greater than that of other magnetic classes.

1.4 Separation in magnetic fluids

The sink and float technique of gravity separation relies on selective levitation and sinking of materials based on their relative densities and that of the separating medium.

In the mid sixties of the last century the application of magnetic fluids as a heavy medium, had been investigated, and it was established that by exposing a magnetic fluid to a non-homogeneous external magnetic field the fluid exhibited an apparent density exceeding densities obtainable with conventional heavy liquids.

The concept of separation of non-magnetic particles suspended in a magnetic fluid is based on the generalized Archimedes law whereby, in addition to the conventional force of gravity acting on the fluid, also a magnetically induced force acts on the fluids. This additional magnetic pull creates a magnetically induced buoyancy force on a particle immersed in the fluid. This buoyancy force can be controlled in a wide range of values and materials as dense as 20000 kg/m^3 or higher can float in such a fluid.

A schematic diagram of the process of separation in magnetic fluids is shown in Fig. 1.3. Permanent magnets or electromagnets are used to generate a non-homogeneous magnetic field in the separation gap. The desired pattern of the magnetic field and its gradient is achieved by shaping the pole tips. A separation chamber placed between the pole-pieces of the magnetic circuit is filled with a magnetic field.

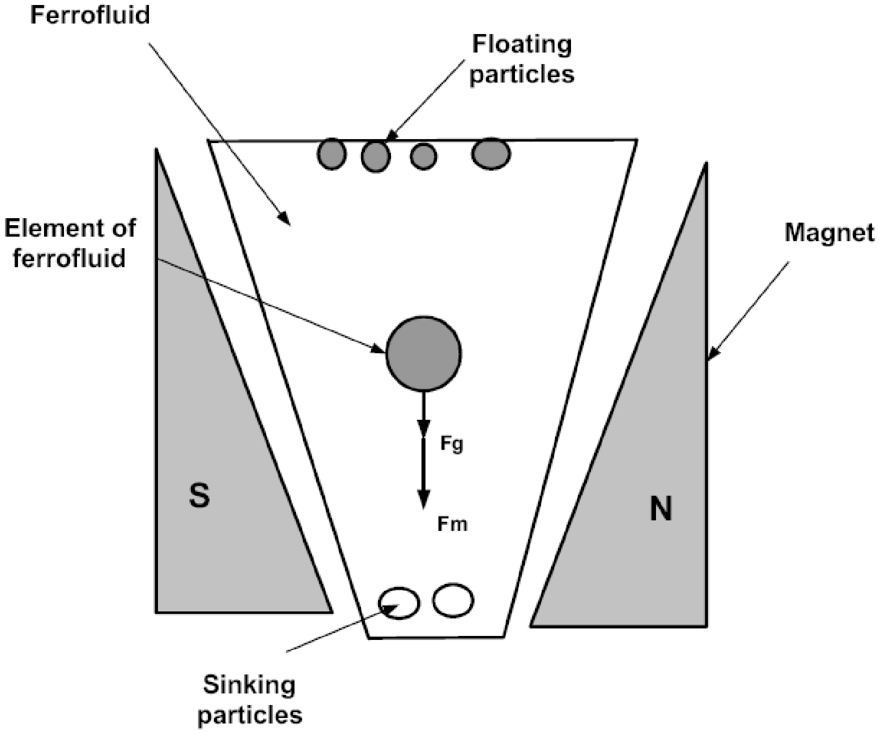


Figure 1.3 - Schematic diagram of the process of separation in magnetic fluids.

1.5 Magnetic fluids: physical characteristics

Magnetic fluids can be divided into two broad classes, namely solutions of paramagnetic salts and ferrofluids.

Paramagnetic liquids, as the name indicates, are paramagnetic in their behaviour: their magnetization increases linearly with increasing magnetic field and their magnetic susceptibility is quite low, of the order of $\chi=5\times10^{-7}$ m^3/kg, and field-independent. In addition to low magnetic susceptibility, some paramagnetic liquids tend to degrade in the presence of light; others tend to crystallize at lower temperatures, while others decompose at elevated temperatures. All such liquids are rather expensive and their recycling is essential, although not easy. The paramagnetic liquids have a high surface tension and do not wet the particles surface adequately.

A magnetic ferrofluid is a stable suspension of sub-domain magnetic particles, often magnetite, in a carrier fluid. Water, hydrocarbon and silicones are used as carrier liquids. The particles, which have an average size of 10 nm, are coated with a stabilizing dispersing agent, which prevents particle agglomeration, even when a strong magnetic field gradient is applied to the ferrofluid.

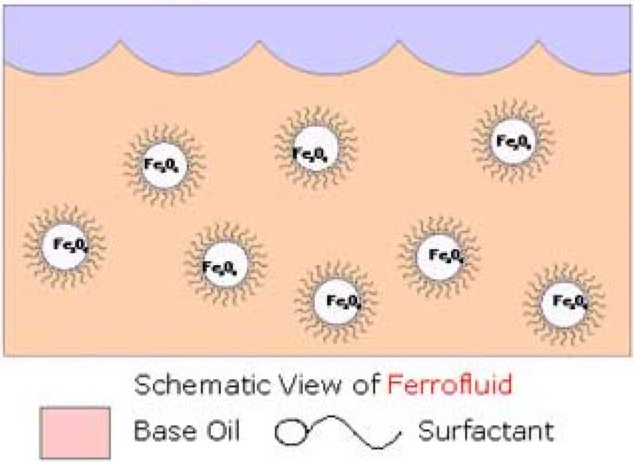


Figure 1.4 - Magnetic particles, with clung surfactant molecules, suspended in a fluid to form a ferrofluid.

In the absence of an external magnetic field, the magnetic moments of individual particles are randomly distributed and the fluid has no net magnetization. When exposed to an external magnetic field, the ferrofluid becomes magnetized and reaches magnetic saturation at moderate magnetic fields. When the applied field is removed, the particles demagnetize rapidly and exhibit typical superparamagnetic behaviour characterized by the absence of coercivity and remanence. A typical magnetization curve of a ferrofluid is shown in Fig. 1.5. It can be seen that a high magnetic field is required to magnetically saturate a ferrofluid containing very small magnetite particles. This is a consequence of the difficulty in aligning the magnetic moments of very small particles.

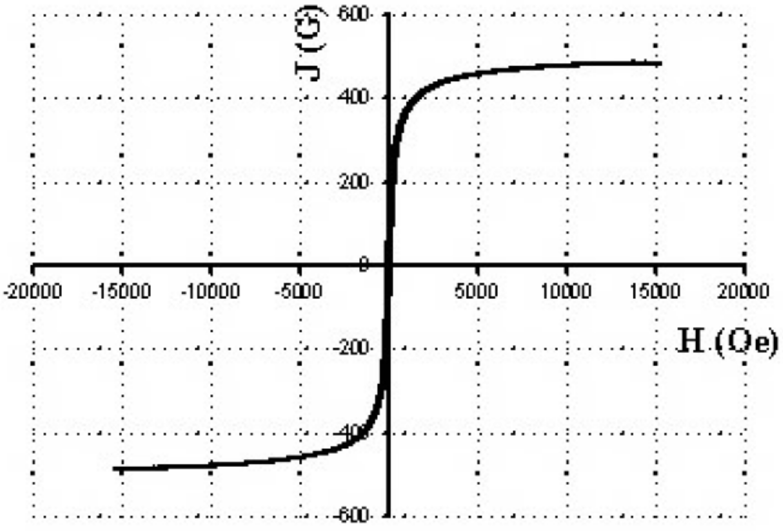


Figure 1.5 - Magnetization curve of a ferrofluid with an average particle diameter 6 nm.

Although very small dimensions of magnetite particles improve the stability of a ferrofluid, the value of saturation magnetization decreases with decreasing particle size, as shown in Fig 1.6.

In weak magnetic fields the main contribution to magnetization is made by the larger particles which are more easily oriented by a magnetic field, whereas the approach to saturation is determined by fine particles, the orientation of which requires large fields.

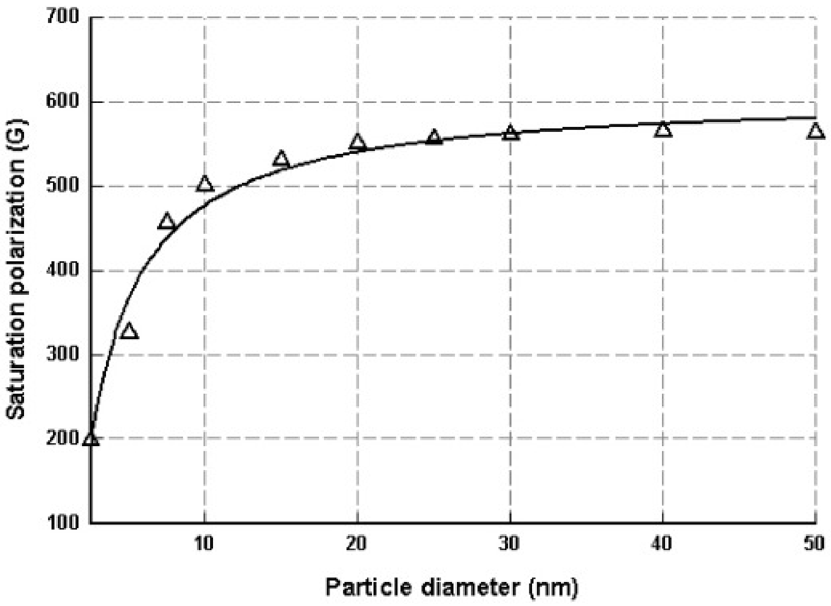


Figure 1.6 - Saturation polarization of ferrofluids as a function of average particle size.

1.5.1 Preparation of ferrofluids

There are two basic methods of preparing a ferrofluid - size reduction and precipitation. Size reduction by wet grinding of ferrite in a ball mill, for a period of 1000 hours or longer, in the presence of a surfactant was developed to produce kerosene-based ferrofluids. Magnetite particles can also be prepared by precipitating the magnetite from a solution of ferric and ferrous ions using an excess of an alkali hydroxide solution. The particles are transferred from the aqueous phase to an organic phase containing a dispersion agent, such as, for instance, oleic acid. Subsequently, the particle dispersion in an organic phase is separated from the aqueous salt residue, filtered, and solvent adjusted to give the desired product concentration.

1.5.2 Viscosity of ferrofluids

The viscosity of a ferrofluid is one of the most important parameters that affect selectivity of separation in ferrofluid. In the absence of a magnetic field, the viscosity of a ferrofluid is greater than that of the carrier liquid as a result of the perturbation of the streamlines by suspended particles.

1.5.3 Stability of ferrofluids

The stability of ferrofluids in gravitational and magnetic fields is one of the fundamental parameters ensuring high selectivity of separation of materials in ferrofluids. Basic criteria for such stability can be obtained by investigating the balance of forces acting on the colloidal magnetic particles suspended in the carrying fluid. The relationship between the randomizing action of the thermal energy and the destabilizing effect of the gravitational field, surface forces, magnetic interaction between the particles and the non-homogeneous magnetic field, and between the particles themselves, determines the conditions under which a ferrofluid is stable.

It is fairly easy to show that while the force of gravity is of limited threat to the segregation of ferrofluids, the effect of magnetic agglomeration and of the field gradient can be eliminated only when the particle diameter is smaller than approximately 8 nm. However, molecular van der Waals forces that arise as a result of fluctuating electric dipole-dipole forces are always present in a colloidal system. It transpires that infinite energy is required to separate a particle pair. Therefore, contact between individual particles must be prevented in order to obtain a stable colloidal suspension. Such a steric stabilization can be achieved by adding a chemical, for instance oleic acid, which can both adsorb on the surface of the particle and be solvated by the carrier liquid. This results in the formation of a bound liquid sheath around each particle. The most commonly used surfactant give a surface layer thickness of 2 nm to 3 nm.

The stability of kerosene-based ferrofluids used in ferrohydrostatic separators extend over periods as long as one year or longer. However, water-based ferrofluids usually contain particles somewhat larger than the particle in organic carriers. The destabilizing effect of magnetic agglomeration and the influence of the gravitational field might reduce the long-term stability that dispersants are not as effective as in organic carrier fluids.

1.5.4 The effect of temperature

A ferrofluid is, over a period of time, exposed to an increasing temperature as a result of the temperature increase in the windings of the electromagnet. The temperature increase results in an increase in the volume, and a decrease in the physical and apparent densities of the ferrofluid, at a constant concentration of magnetite. The change of the apparent density of a ferrofluid with temperature variation is illustrated in Fig. 1.7.

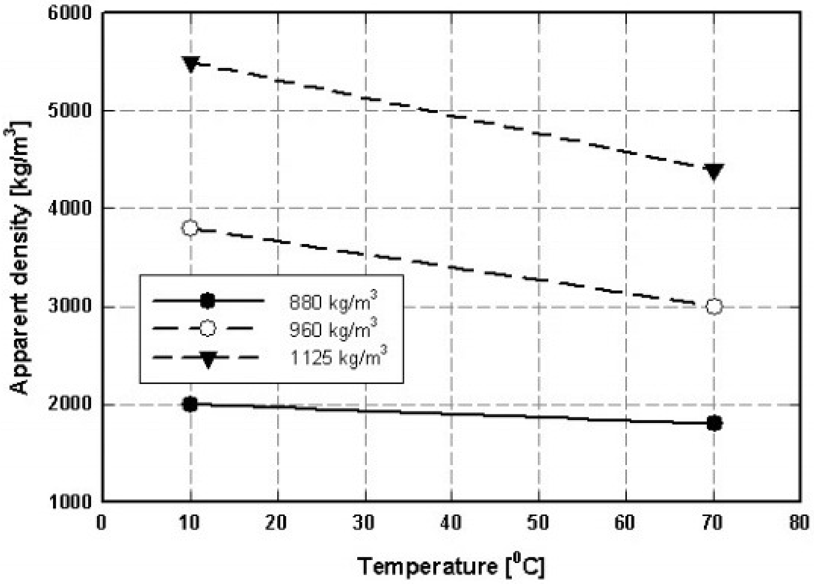


Figure 1.7 - The dependence of the apparent density of ferrofluid on temperature, for various physical densities of the ferrofluid.

In addition to density, magnetic susceptibility also undergoes changes when the temperature of the fluid changes. It was observed that a temperature increase by 15°C results in the reduction of the magnetic susceptibility of the kerosene-based ferrofluid by 7% to 15%, depending upon the magnetic field strength to which the ferrofluid is exposed.

It is clear that temperature control of the ferrofluid and of the working environment in which a ferrohydrostatic separator operates, are essential for accurate performance of the equipment.

In this project the temperature will not affect the characteristic of the ferrofluid, because we are working on lab scale.

1.5.5 Ferrofluid recovery and recycling

In order to keep the running costs of ferrohydrostatic separators low, it is essential that the ferrofluid be recovered and recycled. At the same time, from the environmental point of view, it is imperative to remove tracers of ferrofluid from the products of separation.

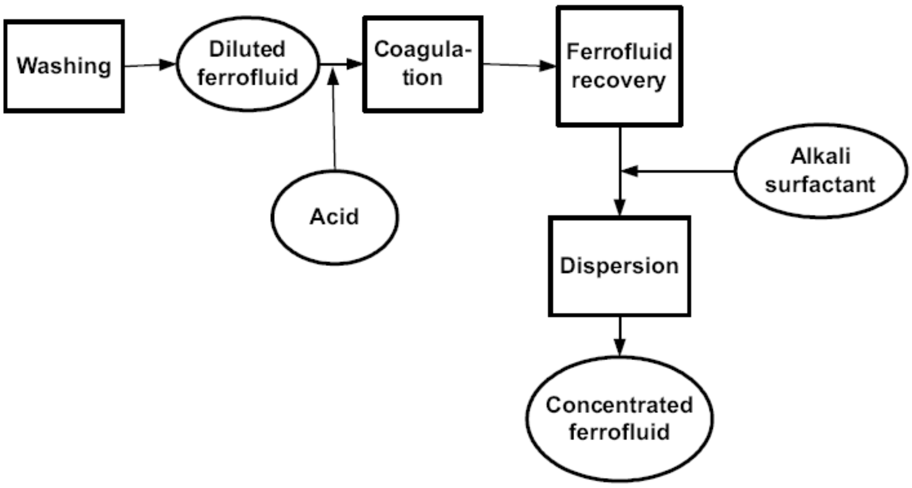


Figure 1.8 - Recovery of water-based ferrofluid.

A water-based ferrofluid adhering to the products of separation can be easily removed by washing the material with water. After the products of separation are washed with water, the diluted suspension is acidified to change the surfactant, providing the secondary adsorption layer, to free acid. A thickener and a centrifugal separator can then be used to separate flocks from the excess water due to the washing process. The concentrated flocks thus obtained are re-dispersed as a concentrated ferrofluid by adding alkali and lost surfactant. The loss of ferrofluid in this process is claimed to be about 1% of the feed by weight. Diluted water-based ferrofluid can be re-concentrated also by ultrafiltration, a slow and potentially onerous process.

1.5.6 Ferrofluid applications

Electronic devices

Ferrofluids are used to form liquid seals (ferrofluidic seals) around the spinning drive shafts in hard disks. The rotating shaft is surrounded by magnets. A small amount of ferrofluid, placed in the gap between the magnet and the shaft, will be held in place by its attraction to the magnet. The fluid of magnetic particles forms a barrier which prevents debris from entering the interior of the hard drive. Ferrofluids are also used in many high-frequency speaker drivers (tweeters) where they provide heat conduction from the voice coil to the surrounding assembly as well as mechanical damping to reduce undesired resonances. The ferrofluid is kept in place in the magnetic gap due to the strong magnetic field and is in contact with both the magnetic surfaces as well as the coil.

Mechanical engineering

Ferrofluids have friction-reducing capabilities. If applied to the surface of a strong enough magnet, such as one made of neodymium, it can cause the magnet to glide across smooth surfaces with minimal resistance.

Ferrari uses ferrofluid in some of their car models to improve the capabilities of the suspension. The suspension can instantly be stiffened or softened by an electromagnet, controlled by a computer.

Defense

The United States Air Force introduced a Radar Absorbent Material (RAM) paint made from both ferrofluidic and non-magnetic substances. By reducing the reflection of electromagnetic waves, this material helps to reduce the Radar Cross Section of aircraft.

Aerospace

NASA has experimented using ferrofluids in a closed loop as the basis for a spacecraft's attitude control system. A magnetic field is applied to a loop of ferrofluid to change the angular momentum and influence the rotation of the spacecraft.

Analytical Instrumentation

Ferrofluids have numerous optical applications due to their refractive properties; that is, each grain, a micromagnet, reflects light. These applications include measuring specific viscosity of a liquid placed between a polarizer and an analyzer, illuminated by a helium-neon laser.

Medicine

In medicine, a compatible ferrofluid can be used for cancer detection. There is also much experimentation with the use of ferrofluids to remove tumors. The ferrofluid would be forced into the tumor and then subjected to a quickly varying magnetic field. This would create friction, yielding heat, due to the movement of the ferrofluid inside the tumor which could destroy the tumor.

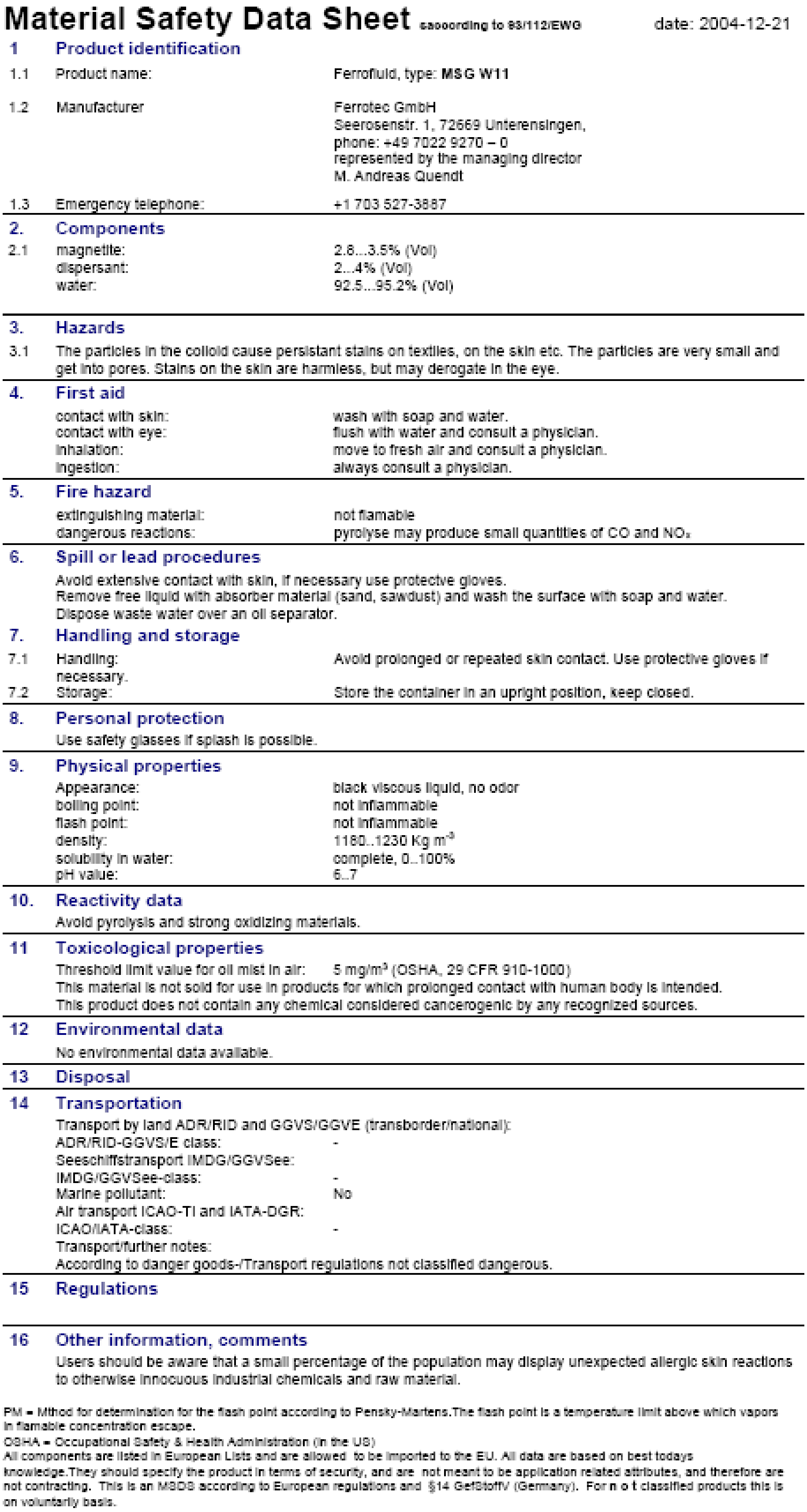
Heat transfer

An external magnetic field imposed on a ferrofluid with varying susceptibility, e.g., due to a temperature gradient, results in a non-uniform magnetic body force, which leads to a form of heat transfer called thermomagnetic convection. This form of heat transfer can be useful when conventional convection heat transfer is inadequate, e.g., in miniature microscale devices or under reduced gravity conditions.

Material Recycling

Ferrofluid has a unique property in that its apparent density can be increased by applying a magnetic field to the ferrofluid. This physical characteristic creates the ability to separate objects of different density through floatation or sinking. Ferrofluids have been used for years in material separation processes in the mining industries, although with limited economic advantage.

1.5.7 Safety data sheet of the ferrofluid used in this project



Material Safety Data Sheet saccording to 93/112/EWG

date: 2004-12-21

1 Product identification

1.1	Product name:	Ferrofluid, type: **MSG W11**
1.2	Manufacturer	Ferrotec GmbH Seerosenstr. 1, 72669 Unterensingen, phone: +49 7022 9270 – 0 represented by the managing director M. Andreas Quendt
1.3	Emergency telephone:	+1 703 527-3887

2. Components

2.1	magnetite:	2.8...3.5% (Vol)
	dispersant:	2...4% (Vol)
	water:	92.5...95.2% (Vol)

3. Hazards

3.1 The particles in the colloid cause persistant stains on textiles, on the skin etc. The particles are very small and get into pores. Stains on the skin are harmless, but may derogate in the eye.

4. First aid

contact with skin:	wash with soap and water.
contact with eye:	flush with water and consult a physician.
inhalation:	move to fresh air and consult a physician.
ingestion:	always consult a physician.

5. Fire hazard

extinguishing material:	not flamable
dangerous reactions:	pyrolyse may produce small quantities of CO and NO_x

6. Spill or lead procedures

Avoid extensive contact with skin, if necessary use protectve gloves.
Remove free liquid with absorber material (sand, sawdust) and wash the surface with soap and water.
Dispose waste water over an oil separator.

7. Handling and storage

7.1	Handling:	Avoid prolonged or repeated skin contact. Use protective gloves if necessary.
7.2	Storage:	Store the container in an upright position, keep closed.

8. Personal protection

Use safety glasses if splash is possible.

9. Physical properties

Appearance:	black viscous liquid, no odor
boiling point:	not inflammable
flash point:	not inflammable
density:	1180..1230 Kg m^{-3}
solubility in water:	complete, 0..100%
pH value:	6..7

10. Reactivity data

Avoid pyrolysis and strong oxidizing materials.

11 Toxicological properties

Threshold limit value for oil mist in air: 5 mg/m³ (OSHA, 29 CFR 910-1000)
This material is not sold for use in products for which prolonged contact with human body is intended.
This product does not contain any chemical considered cancerogenic by any recognized sources.

12 Environmental data

No environmental data available.

13 Disposal

14 Transportation

Transport by land ADR/RID and GGVS/GGVE (transborder/national):

ADR/RID-GGVS/E class:	-
Seeschiffstransport IMDG/GGVSee:	
IMDG/GGVSee-class:	-
Marine pollutant:	No
Air transport ICAO-TI and IATA-DGR:	
ICAO/IATA-class:	-
Transport/further notes:	

According to danger goods-/Transport regulations not classified dangerous.

15 Regulations

16 Other information, comments

Users should be aware that a small percentage of the population may display unexpected allergic skin reactions to otherwise innocuous industrial chemicals and raw material.

PM = Mthod for determination for the flash point according to Pensky-Martens.The flash point is a temperature limit above which vapors in flamable concentration escape.
OSHA = Occupational Safety & Health Administration (in the US)
All components are listed in European Lists and are allowed to be imported to the EU. All data are based on best todays knowledge.They should specify the product in terms of security, and are not meant to be application related attributes, and therefore are not contracting. This is an MSDS according to European regulations and §14 GefStoffV (Germany). For not classified products this is on voluntarily basis.

1.6 Magnetic fluids subjected to a magnetic field

1.6.1 Apparent density of a magnetic fluid

There are two dominant forces acting on a volume of the magnetic fluid, placed in an external non-homogeneous magnetic field, namely the force of gravity and the magnetic traction force.

The total force F_f on the magnetic fluid of volume V_f can be written as:

$$\vec{\mathrm{F}}_{\mathrm{f}} = \vec{F}_g + \vec{F}_m = \rho_f V_f \vec{g} + \frac{1}{\mu_0} k_f V_f B \nabla B \qquad (1.10)$$

where ρ_f is the physical density of the magnetic fluid and k_f is the volume magnetic susceptibility of the magnetic fluid.

For a ferromagnetic ferrofluid, the magnetic force can be expressed as

$$\vec{F}_m = \frac{1}{\mu_0} J_f V_f \nabla B \qquad (1.11)$$

where J_f is the magnetic polarization of the ferrofluid.

When the field gradient is parallel with the gravitational force and of the same sense, eqs. (1.10) and (1.11) can be rearranged, as

$$\vec{\mathrm{F}}_{\mathrm{f}} = V_f \vec{g} \left(\rho_f + \frac{J_f}{\mu_0 g} \nabla B \right) \qquad (1.12)$$

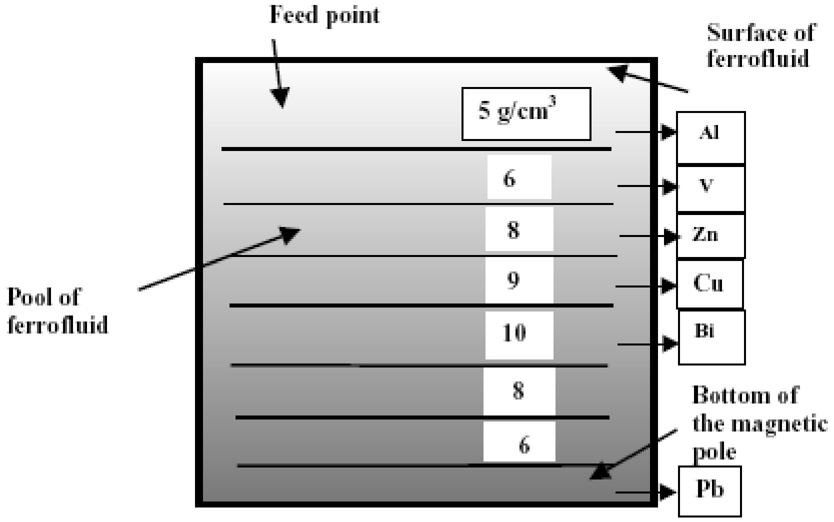


Figure 1.9 - Distribution of the apparent density of ferrofluid. Recovery of various non-ferrous metals at different positions along the vertical axis is indicated.

The expression in parentheses can be viewed as an apparent density ρ_a of a magnetic medium exposed to and external non-homogeneous magnetic field:

$$\rho_a = \rho_f + \frac{J_f}{\mu_0 g}\nabla B \qquad (1.13)$$

In more general case, when the field gradient makes an angle α with gravity, eq. (1.13) becomes:

$$\rho_a = \rho_f + \frac{J_f}{\mu_0 g}\nabla B\cos\alpha \qquad (1.14)$$

1.6.2 A particle suspended in a magnetic fluid

A particle suspended in a magnetic fluid is acted upon by several forces illustrated in Fig. 1.10.

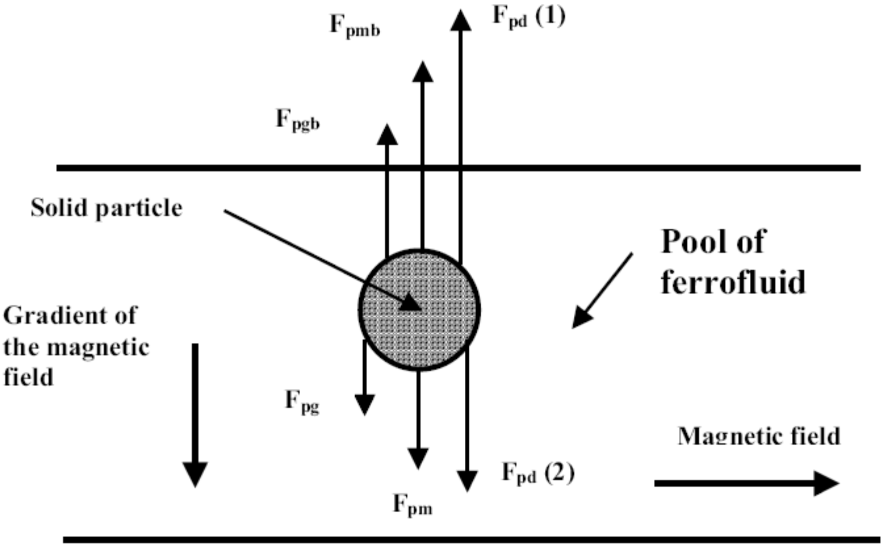


Figure 1.10 - Forces acting on a particle in a stationary ferrofluid, placed in a non-homogeneous magnetic field.

The force of gravity is given by:

$$\vec{F}_{pg} = \rho_p V_p \vec{g} \qquad (1.15)$$

while the magnetic traction force is

$$\vec{F}_{pm} = \frac{1}{\mu_0} k_p V_p B \nabla B \qquad (1.16)$$

where k_p is the volume magnetic susceptibility of the particle.

Such a particle experiences a loss of its weight as a result of two buoyancy forces acting on the particle. The first buoyancy force is the classical Archimedes gravity-related force:

$$\vec{F}_{pgb} = \rho_f V_p \vec{g} \qquad (1.17)$$

The other force is the magnetically induced buoyancy force due to the magnetic traction force acting on the ferrofluid:

$$\vec{F}_{pmb} = \frac{1}{\mu_0} V_p J_f \nabla B \qquad (1.18)$$

The net vertical force on a particle suspended in a ferrofluids and acted upon by a non–homogeneous magnetic field with vertical gradient can thus be written:

$$\vec{F}_p = \vec{F}_{pg} + \vec{F}_{pm} + \vec{F}_{pgb} + \vec{F}_{pmb} \qquad (1.19)$$

or, in an explicit form:

$$\vec{F}_p = V_p\left(\rho_p - \rho_f\right)\vec{g} + \frac{\nabla B}{\mu_0} V_p\left(k_p B - J_f\right) \qquad (1.20)$$

Defining the effective cut-point density ρ_{cp} for separation as that particle density ρ_p for which $F_p = 0$ (i.e. equilibrium of the forces acting on the particle), eq. (20) yields:

$$\rho_a = \rho_f + \frac{\nabla B}{g}\left(J_f - k_p B\right)\cos\alpha \qquad (1.21)$$

For non magnetic particles $k_p = 0$ and eq. (1.14) reduces to:

$$\rho_a = \rho_f + \frac{J_f}{\mu_0 g}\nabla B \cos\alpha \qquad (1.22)$$

where α is the angle between the vectors of the gravitational force and the field gradient. When the force of gravity and the gradient of the magnetic field are parallel, eq. (1.22) becomes:

$$\rho_a = \rho_f + \frac{J_f}{\mu_0 g}\nabla B \qquad (1.23)$$

which is equivalent to eq. 1.(13).

Equation (1.23) can be rewritten as:

$$\rho_a = \rho_f + \frac{M_f}{g} \nabla B \qquad (1.24)$$

where M_f is the magnetization of the fluid.

It can be seen that for non-magnetic particles, the density cut-point is equal to the apparent density of the ferrofluid. Particles whose density ρ_p are smaller than the apparent density of the ferrofluid ($\rho_p < \rho_a$) will float in the ferrofluid, while particles with density greater than the apparent density of the ferrofluid ($\rho_p > \rho_a$) will sink. Trajectories of sink and float particles in a stationary ferrofluid placed in a non –homogeneous magnetic field are shown in Fig. 1.11.

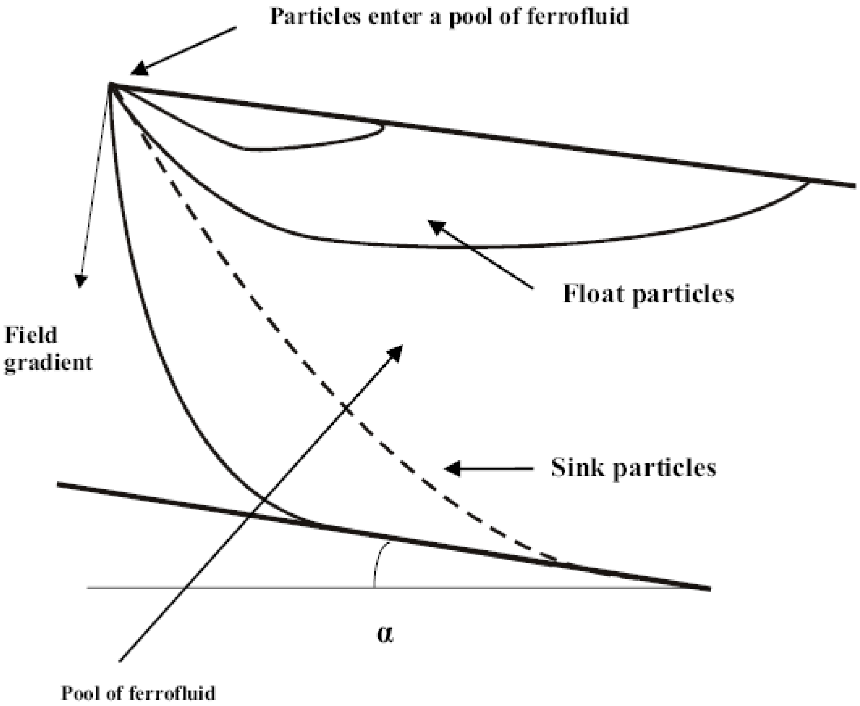


Figure 1.11 - Trajectories of float and sink particles in a stationary ferrofluid placed in a non-homogeneous magnetic field.

1.6.3 The effect of the hydrodynamic drag

In many applications of ferrohydrostatic separation it is legitimate to ignore the effect of the hydrodynamic drag. For small particles, however, the influence of the drag on the cut-point density can be significant.

If we assume that the Stokes law applies, the hydrodynamic drag is given by:

$$\vec{F}_d = 6\pi\eta b\left(\vec{v}_f - \vec{v}_p\right) \qquad (1.25)$$

where η $[Pa \cdot s]$ is the dynamic viscosity of the fluid and v_f and v_p are velocities of the fluid and the particle, respectively.

By including this drag in the expression of the total force, the equilibrium of forces on a non-magnetic particle yields:

$$\rho_a = \rho_f + \frac{J_f}{\mu_0 g}\nabla B + \frac{9\eta v}{2gb^2} \qquad (1.26)$$

Equation (1.18) applies to a particle that is moving vertically downwards, i.e. the hydrodynamic drag F_{pd} acts on the particle. Such a particle is either a sink particle, i.e. a particle whose density is greater than ρ_a, or a float particle, that is temporally moving downwards because of the non-zero initial velocity with which it entered the fluid, as shown in Fig. 1.5.

Once a float particle reaches its terminal velocity (equals to zero), it will reverse the direction of its motion and will start moving upwards. At that point the opposite hydrodynamic drag F_{pd} will be acting on the particle and the particle will experience an apparent density given by:

$$\rho_a = \rho_f + \frac{J_f}{\mu_0 g}\nabla B - \frac{9\eta v}{2gb^2} \qquad (1.27)$$

Therefore, it becomes clear that, in general terms, the presence of the hydrodynamic drag increases the cut point density for sinking particles, i.e. sink particles or float particles in their initial phase of motion within the ferrofluid. For particles reporting to the float fraction, however, the hydrodynamic drag decreases the cut point density.

It can be found from eq. (1.26) that for particles greater than 1mm the hydrodynamic drag can be neglected and the cut point density is independent of particle size, and is given by eq. (1.23). However, by inclusion of the hydrodynamic drag, the cut point density begins to deviate, for particles smaller than 1 mm, from its “large particle value”, as illustrated in Fig.1.12.

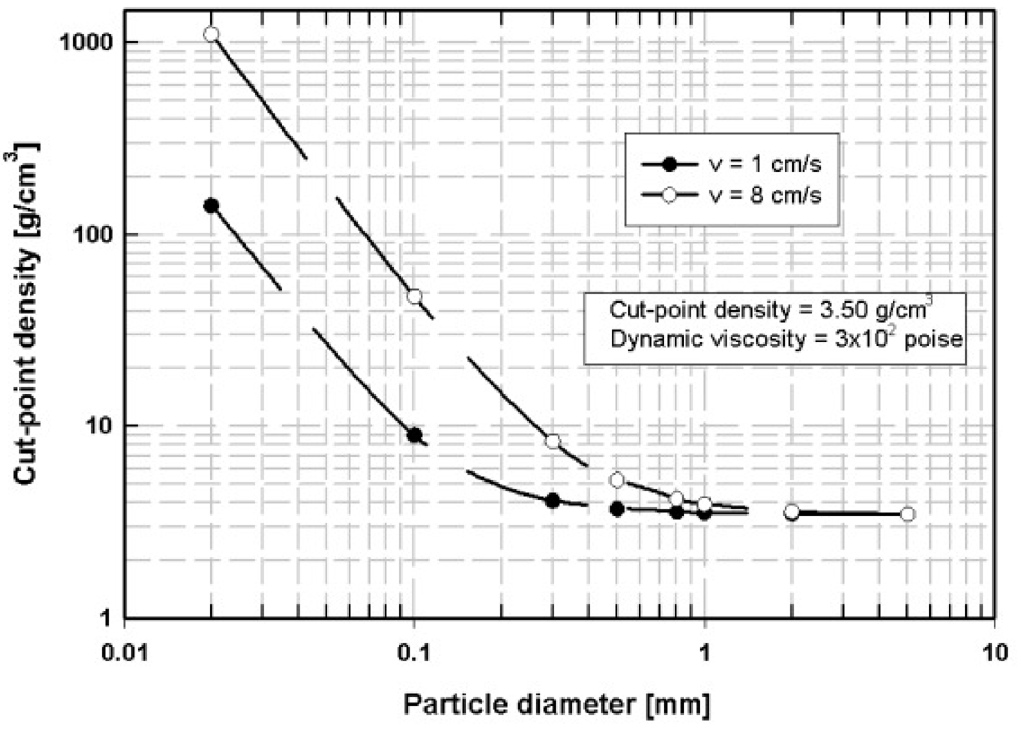


Figure 1.12 - The effect of hydrodynamic drag on cut-point density, for two particle velocities. The nominal “large particle” cut-point density ρ_{cp} = 3500 kg/m^3.

Fig. 1.13 shows the inaccuracy in the cut-point density introduced by ignoring the hydrodynamic drag.

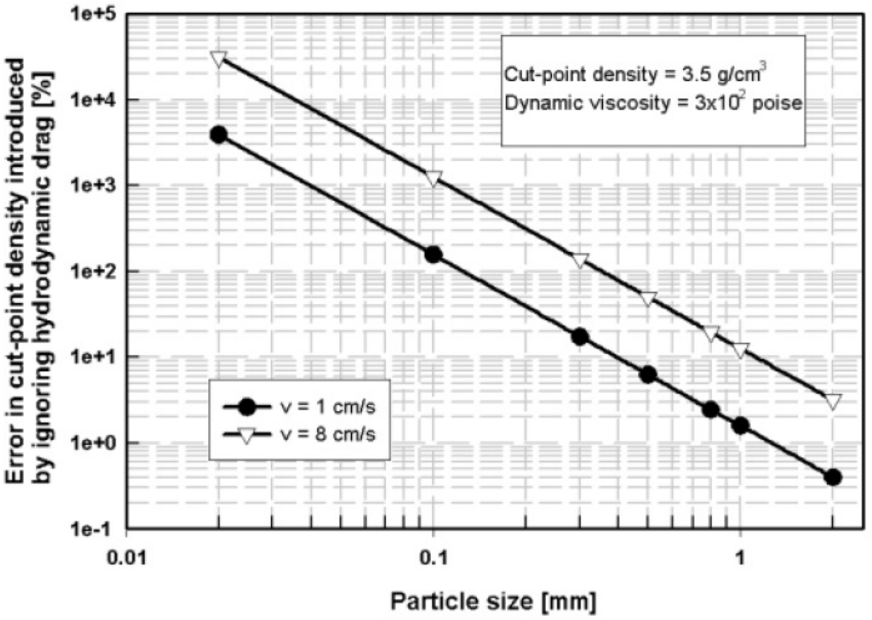


Figure 1.13 - The inaccuracy in cut-point density introduced by ignoring hydrodynamic drag, for two different particle velocities. The nominal cut-point density ρ_{cp} = 3500 kg/m^3.

1.6.4 Interaction of particles during separation

The analysis of the particle motion in a ferrofluid assumed that particles were non-interacting. This simplification ignores, however, the fact that non-magnetic particles suspended in a magnetic fluid possess surface magnetic charges as a result of magnetization of the surrounding fluid. It was determined, theoretically and experimentally, that non-magnetic particles, placed in a magnetized ferrofluid, attracted one another in the direction parallel to the direction of magnetic field and repelled one another in the perpendicular direction.

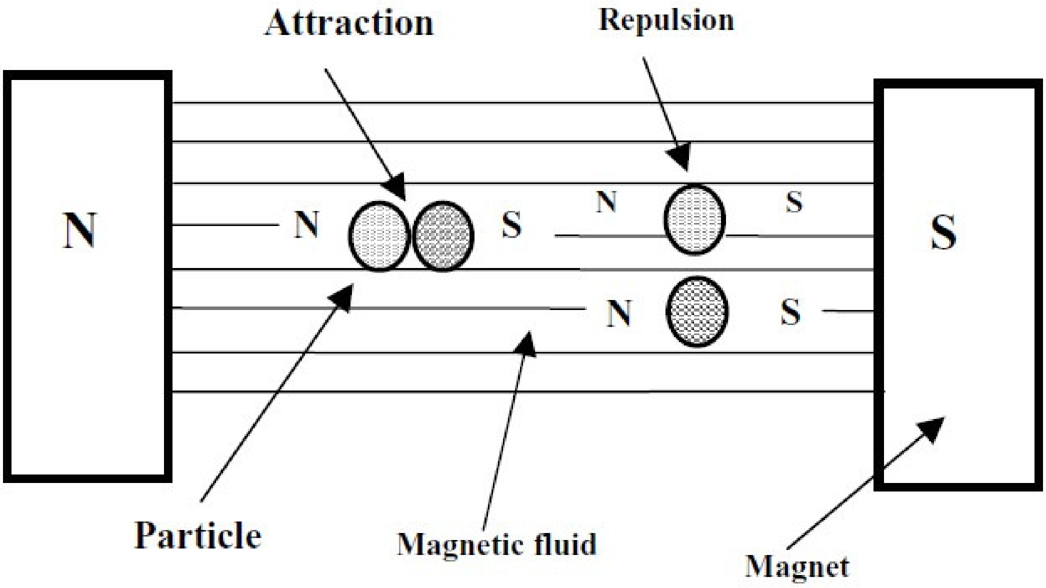


Figure 1.14 - Interaction between non-magnetic particles in a magnetized magnetic fluid.

The situation is depicted in Fig. 1.8. The attractive force increases with increasing density of the ferrofluid and the magnetic field strength. The attractive interaction was found to reduce the selectivity of separation of non-magnetic particles in a magnetic fluid.

1.7 The Magnetic Density Separation (MDS)

Many designs of magneto-hydrostatic separators are known from the literature. The most popular type of separator consists of a cavity between two curved polar pieces of an electromagnet, in which the field lines run mainly horizontal and the concentration of field lines (the magnetic induction) increases towards the bottom of the cavity. The curved poles create a field that produces an almost constant effective density of the magnetic fluid. An important problem of these separators is that magnetic contaminants are attracted to the poles. Another important point is the relatively complex geometry of the cavity and the difficulties of up scaling.

The approach to magneto-hydrostatic separation is to create a medium with a cut-density that is not a constant but varies with the vertical coordinate.

For a magnetic induction that varies exponentially with z,

$$\left|B\right|(x,y,z) = B_0\, \mathrm{e}^{-2\pi z/w} \qquad (1.28)$$

The effective medium density varies with z as well:

$$\rho_a = \rho_f + \frac{2\pi M B_0}{g w} e^{-2\pi z/w} \qquad (1.29)$$

A field like that of Eq. (1.28) can be created by a series of alternating magnetic poles in a plane geometry:

$$\begin{aligned} B_x(x,y,z) &= B_0\, \mathrm{e}^{-2\pi z/w} \sin(2\pi x/w) \\ B_z(x,y,z) &= B_0\, \mathrm{e}^{-2\pi z/w} \cos(2\pi x/w) \end{aligned} \qquad (1.30)$$

The magnetic density separator segregates the feed into layers of different materials, with each material floating on a distance from the magnet according to its density and the apparent density of the fluid.

If two materials of density ρ_1 and ρ_2 need to be separated, the segregation distance:

$$z_1 - z_2 = \frac{w}{2\pi} \ln\left(\frac{\rho_2 - \rho}{\rho_1 - \rho}\right) \qquad (1.31)$$

must exceed the maximum particle size of the feed. This is achieved by selecting a proper wavelength w of the field for the application.

1.8 The magnet

Professor Rem of the Delft University of Technology calculated a configuration of magnets that would produce such a field. Magnet manufacturers Bakker Magnetics, who specializes in the manufacture of complex magnet systems, produced the configuration. The main ingredient of the magnet plate is a set of extremely powerful permanent iron neodymium-borium magnets. The field strength just above the magnets is 1 Tesla, which is strong for a permanent magnet. The magnets are mounted in a ‘frustrated’ configuration, which means that they are out of balance and subject to large forces acting between them. The whole assembly is covered by a steel plate to protect researchers from being hit by any magnet fragments that may become detached from the main mass. The magnet configuration calculated by Professor Rem is a patent, and is thus secret.

The apparent density of the fluid depends solely on the vertical distance from the magnet’s surface. All density lines run horizontal, creating an apparent density range which is the same everywhere on the magnet. The magnet used in this project created however a density profile in which a wavy pattern starts to appear when approaching the magnet’s surface: a few centimeters above the magnet the density lines are horizontal, but closer to the surface waves are appearing whose amplitudes are increasing towards the magnet’s surface. Since particles will settle in the trough of a wave, the floating height of particles decreases when this height lies in the wavy part of the density profile. The closer the floating height is to the magnet’s surface, the larger this decrease will be. In the first few centimeters above the magnet the wavy pattern has even such large amplitudes that low density trenches are created: relative light particles will sink when entering the fluid. Is thus important that the particles that are to be extracted hover at a vertical height where the effect of the trenches cannot be seen anymore.

Chapter 2

Magnetic density separator

2.1 Magnetic density separator: original layout

A separator, which is able to separate multiple density fractions at once, was designed. The main part of the separator is a brass vibrating gutter. Fluid and non-ferrous materials are led into the gutter, straight into the magnetic field where the separation begins. At the end of the magnetic field the different density fractions are pumped towards a sieve. Here the materials remain behind and the fluid is collected and circulated.

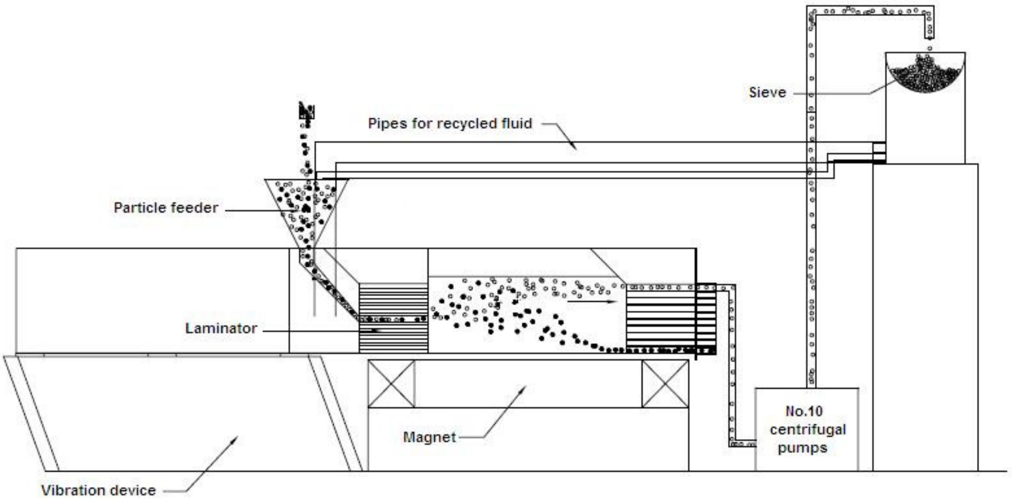


Figure 2.1 - Process of Magnetic Density Separation (MDS): original layout.

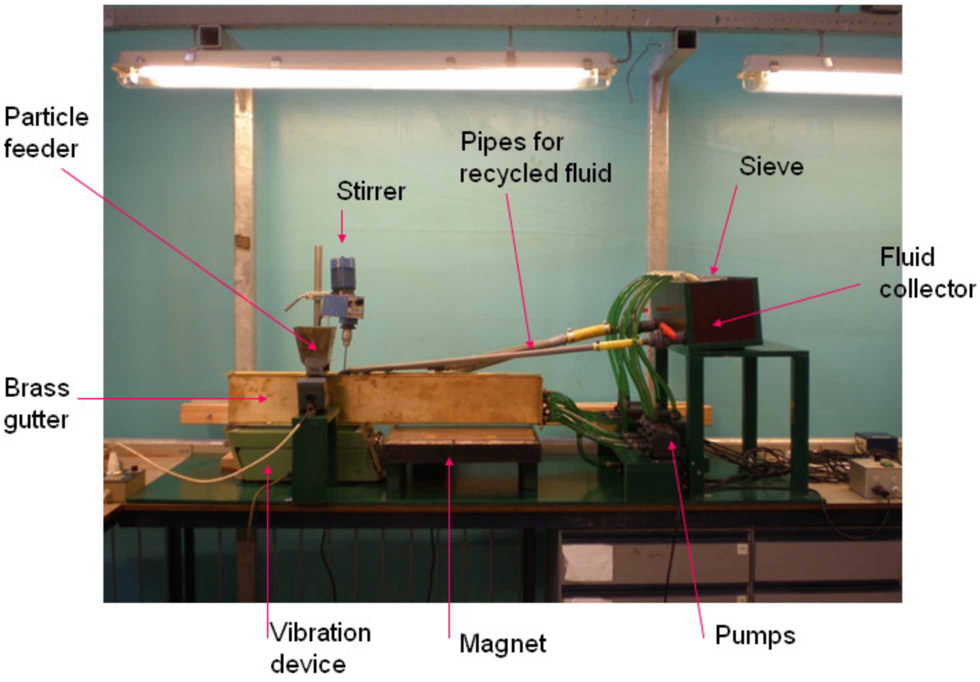


Figure 2.2 - Process of Magnetic Density Separation (MDS): layout and equipment.

The separation process consists of five steps:

1. Fluid that is collected at the end of the separation process is circulated back to the beginning, where it is led through a laminator in order to create a laminar flow. The laminator is a 100 mm long grid with rectangular openings that leads the fluid into the magnetic field.
2. The minerals are fed into a section of the gutter, where they are mixed with a small amount of magnetic fluid. A stirrer is used to make sure the samples are drawn downwards to the particle inlet. The section is connected to the main separation area by a hose which leads the minerals through the laminator in a special inlet.

Figure 2.3 - Inlet of materials and laminator.

3. Once in the separation area, the minerals move towards their floating heights. During the separation the gutter vibrates at high frequency with low amplitude. This way the minerals do not get stuck to the bottom or side walls of the gutter.
4. At the end of magnetic field the materials are separated permanently by outlets, each one 10 mm high. The fluid and the minerals are led towards a

Figure 2.4 - Outlets sections.

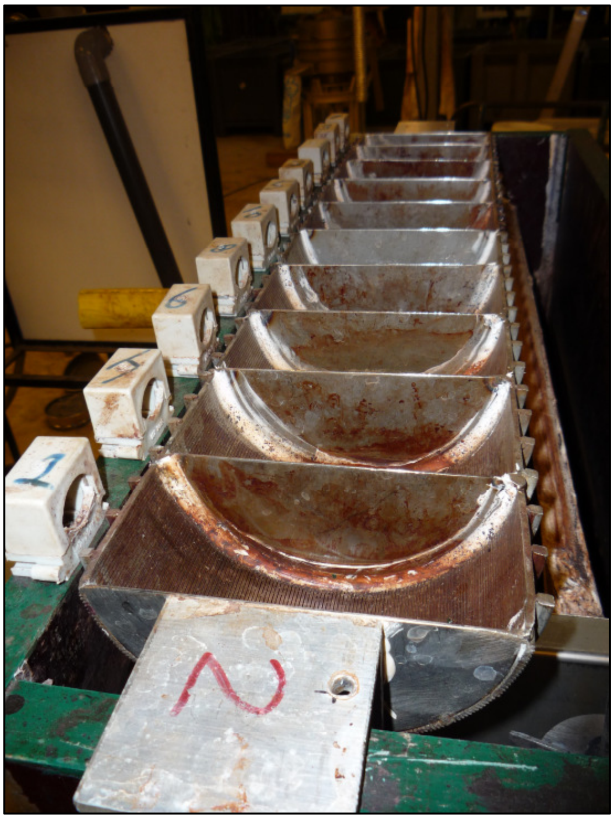


Figure 2.5 - Sieve divided into 10 sections.

small opening. Each opening has a separate pump, which pumps the fluid and the particles towards a sieve. The sieve is divided in ten sections, each connected to one outlet.

5. The different fractions are collected in the sieve and the fluid is retrieved in an area, which is connected to the beginning of the separator. The fluid is led back to the separator through a series of pipes. The fluid flow is controlled by two valves.

2.2 First test: separating diamonds from gangue minerals

In its first application the magnetic density separator was used to separate the diamond fraction - represented from 0,5 ÷ 2 mm olivine particles - from other equally small gangue materials. The aim of this test was to extract a single density fraction from the fluid, while all material lighter or heavier is discarded.

2.2.1 Materials

A diamond crystal has a mean density of $3520^{\pm 10}$ kg/m^3. Due to inclusion of gases and minerals this density can range from 3100 ÷ 3600 kg/m^3. To extract all diamonds, material outside the density range of 3100 ÷ 3600 kg/m^3 should be discarded. To ensure a high grade of pureness of the diamond fraction it is important that not too many other minerals report to this fraction. Since hydrostatic magnetic separation can already discard up to 95% of the particles using densities of 2700 ÷ 3100 kg/m^3 and with magnetic density separation being capable of rejecting the heavy minerals (>3600 kg/m^3) as well, using magnetic density separation will only improve the separation results.

The materials used for this test were orthoclase (2515 kg/m^3), calcite (2697 kg/m^3) olivine (3359 kg/m^3) and ilmenite (4710 kg/m^3). Due to its density the olivine was suitable to represent the diamond fraction during the tests. The materials were chosen on the basis of the colour. The distinct colour differences between the minerals can be used to get a first impression on the separation result; X-Ray Fluorescence (XRF) was used to determine the recovery of each mineral in the separation fractions.

2.2.2 The fluid

The fluid used originates from Ferrotec. A magnetization M=13500 A/m and a density ρ_f =1360 kg/m^3 were measured for the pure fluid. To create a suitable density range for separation the magnetic fluid was diluted using water.

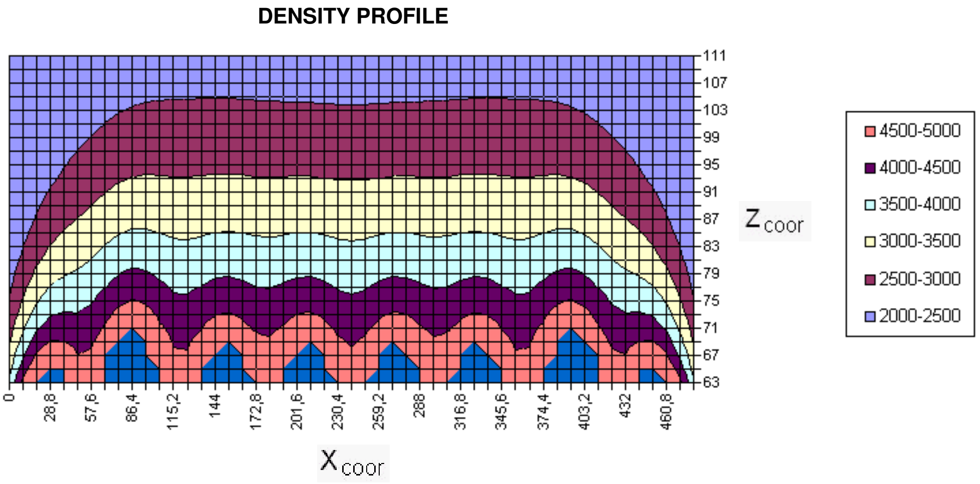


Figure 2.6 - Density profile in a ferrofluid with a dilution factor of 1:3 and a magnetization of 4500 A/m.

It can be seen that low density trenches are present in the first 25 mm above the surface of the magnet. It was therefore decided that the olivine should have a floating height of at least 30 mm so the mineral's particles would not be hindered by the trenches. It was decided to use a fluid with dilution factor 1:3, consisting of one part of magnetic fluid mixed with two parts of water. Theoretically the floating height of olivine in a 1:3 fluid is 40 mm. From experimental floating-test was determined that, even though the wavy pattern in the density profile decreases the floating height of olivine, it still remains over 30 mm.

2.2.3 Time of separation

Based on the theoretical floating height in the 1:3 fluid it was calculated how much time a mineral particle needs to reach its floating height. The 0,5 mm orthoclase particles take the longest time to separate: 0,62 seconds. Since the separation area in the separator is 0,30 m long, the fluid velocity in the separator should be less than 0,30 / 0,62 = 0,48 m/s for all minerals to successfully reach their floating heights.

It should be noted that the olivine particles are inserted at their experimental floating height, so in practice they already float at their extraction height.

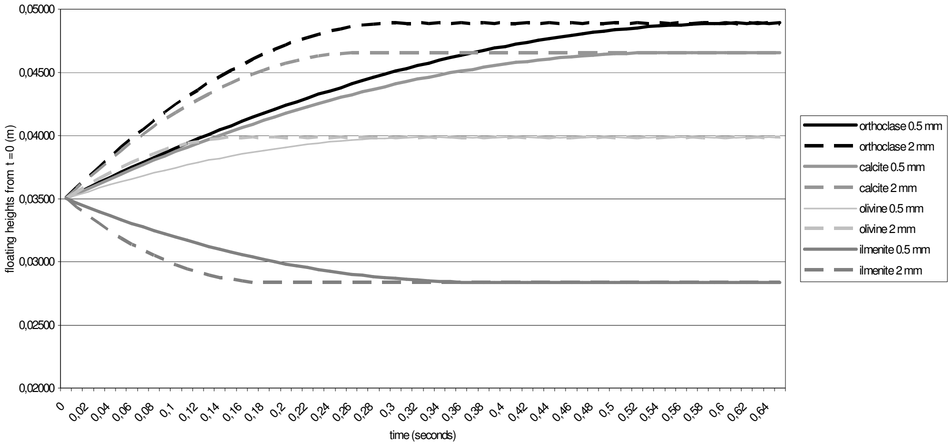


Figure 2.7 - Time for materials to reach their theoretic floating height.

2.2.4 Flow measurements

For magnetic density separation a laminar flow was preferred. If the flow is turbulent, the mineral particles could end up in the wrong density fraction, disrupting the separation process.

To test the flow inside the separator the system was filled with water and a small amount of ink was injected in the main stream at different heights. The ink clouds moved horizontally from inlet toward outlet. This indicated that no misplacement of particles should take place inside the separator due to turbulence.

To measure the flow speed of the magnetic fluid inside the separator, an electromagnetic flow sensor (EM) was used. This sensor can measure in the low velocity range of 0 ÷ 1 m/s and it can measure the velocity at different heights, so a velocity profile through the fluid column in the separation area could be made. Since the EM sensor works with a self generated magnetic field, the measurements could only be done with the magnet removed from under the separator. The fluid velocity was measured at three different locations (about 6 cm behind the laminator, halfway the separation area and about 6 cm in front of the outlets), at four different heights. It was assumed that the velocities measured in magnetic fluid will be comparable to those in water, to which the sensor is calibrated.

One trend is that the fluid velocity decreases with depth. Since the fluid column in the separator is only 10 cm high, the bottom will have a relative large influence on the fluid's velocity. Another observation that can be made is that the amount of fluid transported halfway the laminator is almost the same as the amount of fluid transported near the outlets. To transport about the same amount of fluid velocities at lower heights should decrease.

The reliability of the measurements is low since the amount of fluid transported near the laminator is much lower than the amounts transported at the other two locations. Close to the laminator and near the particle inlet, which is placed at a height of 3 ÷ 4 cm from the magnet's surface, the flow is more turbulent. The large difference with the other two locations can partly be caused by this turbulence. Not only is the EM sensor designed for measurements in laminar flow, its large probe size causes some disturbance in the flow as well. The probe used for the measurements was 3 cm wide, while the separation area was 6 cm wide.

2.2.5 Results

It was found that olivine, calcite and orthoclase ended up in lower separation fractions than predicted. The most olivine and ilmenite ended up in the first two fractions, 1 ÷ 3 cm above the magnet, while a larger part of the lighter calcite and orthoclase were found in fraction three and higher (3 ÷ 6 cm above the magnet). The total recovery of olivine in the first two fraction was 93,6%. This shows a high recovery rate for olivine (and thus diamond fraction).

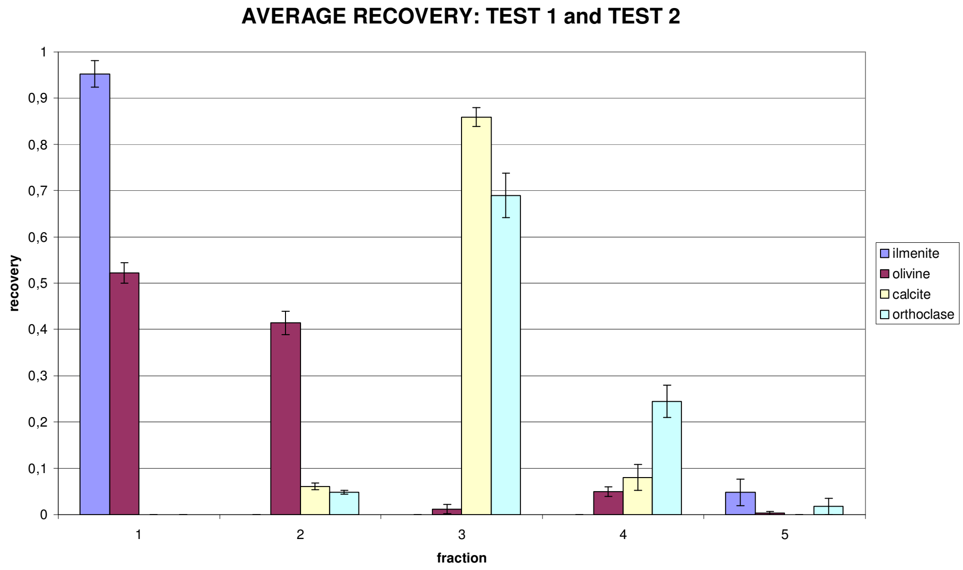


Figure 2.8 - Results about separation test of diamonds.

2.2.6 Problems found during experimentation

The magnet

The apparent density of the fluid depends solely on the vertical distance from the surface of the magnet. All density lines run horizontal, creating an apparent density range which is the same everywhere on the magnet.

The magnet used in this project created however a density profile in which a wavy pattern starts to appear when approaching the magnet's surface: a few centimetres above the magnet the density lines are horizontal, but closer to the surface waves are appearing whose amplitudes are increasing towards the magnet's surface. The floating height of particles decreases when this height lies in the wavy part of the density profile. The closer the floating height is to the magnet's surface, the larger this decrease will be. In the first few centimetres above the magnet the wavy pattern has even such large amplitudes that low density trenches are created: relative light particles will sink when entering the fluid. Is thus important that the particles that are to be extracted hover at a vertical height where the effect of the trenches cannot be seen anymore.

Moreover it was noted that during the lab-scale tests all minerals ended up in lower separation fractions. The lower recovery heights can be explained by the density profile which slopes downwards near the magnet's edges. When particle enter this part of the profile, their floating heights decrease.

The flow

The turbulence near the laminator can be minimized when the particle inlet velocity is matched with the fluid flow through the laminator. This can be done by using pumps to control the return flow instead of letting the fluid flow freely back to the separator through a series of pipes.

The acceleration of the fluid at high levels near the outlets (and thus deceleration of the fluid velocity near the magnet's surface) can be better controlled by regulating the pump separately. All pumps at the outlets are set to the same capacity. Assuming a laminar flow is present in the separation area, the volume of fluid entering the lower pumps is less than the fluid entering the higher pumps. For all pumps to reach the same capacity, the lower pumps need extra fluid. If this fluid is withdrawn from higher fluid levels, this will slow down the fluid that is already flowing at pump level. To avoid this effect it is recommended to use pumps which can be regulated separately, so each pump can extract a certain amount of fluid without disturbing the flow present in the fluid.

With the magnet placed under the separator the effect should be less. It was found that with the magnet placed under the fluid, the fluid velocities will decrease since pumping one litre of pure fluid over a non-magnetic surface takes less time than pumping the same amount of fluid over a magnetic surface. Moreover, since the influence of the magnetic field decrease with vertical distance, the magnet's influence on the fluid velocity will decrease with vertical distance as well.

Air bubbles

A small percentage of ilmenite was recovered in the fifth fraction, while this was not present in the other light fractions. A possible explanation is that these particles were not wetted properly and air bubbles were attached to them during separation.

2.3 Rebuilding of the magnetic density separator

With the first magnetic density separator it was possible to recover diamonds, represented by olivine, from other minerals. In spite of some problems, the results were promising.

The system has been rebuilt, in order to have a more accurate separation. The aim has been to improve the system and to obtain good results with different kind of materials.

2.4 First layout

The flow turbulence was one of the main problems of the previous separator.

At the beginning of the area of separation a weak turbulence is required in order to prevent the interaction among the materials. Then the turbulence should decrease and the particles should be separated according to their own density.

In the new configuration a basin is added beside the separator.

The fluid, collected at the end of the separation process, is circulated back to the new basin before going into the separator. The basin, used as stock of fluid, ensures a decrease of the turbulence. The level of fluid in the basin is stable. The basin is placed above the separator in order to produce a natural flow and to ensure a constant amount of fluid to the system.

From the basin, the fluid is led to the magnetic density separator by a hose. The flow is regulated with one valve.

A small amount of fluid is pumped from the basin to the inlet section of the materials in order to create slurry, which is led to a special inlet and than directly to the area of separation.

The pumps used in this configuration are centrifugal pumps (not self-priming), therefore they must be positioned below the level of the water to become operative.

They take the separated materials from the separator and pump them to the sieve.

These pumps work at 25% of their power in order to ensure the right capacity to the system. The regulation is possible by a power switch.

One further pump is necessary to send the sample to the inlet section of the materials.

Figure 2.9 - Centrifugal pump.

A calculation of the flow parameters can be performed. The fluid chosen for this experiment is a pure ferromagnetic fluid.

Data of the flow though each pipe	
Flow rate (25%)	$Q = 0{,}0415\, l/s = 0{,}0000415\, m^3/s$
Diameter of the pipe	$D = 0{,}01 m$
Cross-sectional area	$A = \pi \left(\frac{D}{2} \right)^2 = 0{,}0000785 m^2$
Mean velocity	$v = \frac{Q}{A} = 0{,}529\, m/s$
Reynolds number	$\mathrm{Re} = \frac{\rho v D}{\mu} = 327{,}018$
Density of the fluid	$\rho = 1156\, kg/m^3$
Dynamic viscosity	$\mu = 1{,}87 \cdot 10^{-2}\, Pa/s$

Data of the flow through each outlet section	
Flow rate (25%)	$Q = 0{,}0415\, l/s = 0{,}0000415\, m^3/s$
Hydraulic diameter	$D_H = \frac{4A}{P} = 0{,}017 m$
Cross-sectional area	$A = W \cdot H = 0{,}0006 m^2$
Width	$W = 0{,}06 m$
Height	$H = 0{,}01 m$
Wetted perimeter	$P = 2 \cdot W + 2 \cdot H = 0{,}14 m$
Mean velocity	$v = \frac{Q}{A} = 0{,}0691 m/s$
Reynolds number	$\mathrm{Re} = \frac{\rho v D}{\mu} = 72{,}6$
Density of the fluid	$\rho = 1156\, kg/m^3$
Dynamic viscosity	$\mu = 1{,}87 \cdot 10^{-2}\, Pa/s$

2.4.1 Results

This new configuration has been tested in order to decrease the turbulence in the separator. Despite that, many longitudinal waves are still visible. These waves can affect the separation of the materials: the particles, dragged by the waves, can end up in the wrong fraction.

The quantity of water in the system has been investigated. The level of the water is not stable and it is always too low, so that the higher sections are not filled and the respective pumps are not fed continuously. The quantity of water in the system has been increased, but the flow is always oscillating and turbulent.

After some tests it has been found that the turbulence depends on the intermittent work of the pumps. The pumps can not be regulated separately, therefore they have been regulated by a device that interrupts the electricity. It means that they switch on and off continuously, so that the flow itself is interrupted.

A further test with only three pumps working at 100% of their power (without changing the power) has been carried out. The flow becomes more laminar and no waves can be seen on the surface.

It still remains the problem of the instable fluid level. Moreover it is always very difficult to regulate the whole system with one valve and invariable pumps.

2.5 Second layout

A second layout has been set up. The aim has been to reduce as much as possible the turbulence and to find a way to keep the level of the fluid stable in the area of separation.

The basin, placed beside the separator, is removed because it is not helpful in the decrease of the turbulence. In fact, it has been discovered the turbulence depends on the intermittent working of the pumps. New pumps, which can be regulated separately, have been used. At the same time the problem of the level of the fluid in the system has been analyzed.

A closed area has been created before the area of separation in order to keep the level of the fluid stable. A plastic cover closes the upper side of the inlet area. The lid is equipped with three holes for the inlet of the fluid and the materials.

Figure 2.10 - The plastic lid with the holes for the inlet of the fluid (left) and the inlets of the slurry of fluid and materials (right).

The separator outlet is settled with ten sections. Each two sections there is a pump that leads the fluid towards a sieve. By the previous test it has been found that the higher sections were not filled with enough fluid. Therefore in that configuration the two higher sections are not connected with a pump.

Because of delay in the delivery of new pumps, the old centrifugal pumps have been used. Four pumps work at 100% of their power and they can not be regulated separately.

The geometry of the sieve is not changed. But only five sections of the sieve are used.

The inlet of the materials is placed under the sieves. The materials and a small amount of fluid, coming from the lowest pump, are mixed together in order to obtain a slurry. The slurry is led through a pipe, which goes through the lid and is connected directly with a special inlet to the separation area.

The fluid is led to the MDS through a pipe that is connected to the lid. The magnetic fluid fills all the closed area behind the laminator.

2.5.1 Results

Some simple tests with plastic particles have been carried out. It is possible to see (without any special measurement) that the flow is not perfectly laminar.

The samples are fed manually at the beginning of the area of separation. The materials float for a short period. When they arrive in the middle of the separation area, their velocity increases. The separation happens in a short time and the trajectory of the particles is not regular.

In order to achieve a laminar flow and to avoid sudden acceleration of the velocity it is necessary to find a new configuration of the area behind the laminator.

2.6 Third layout

A new configuration is necessary in order to solve the problems of the previous layouts.

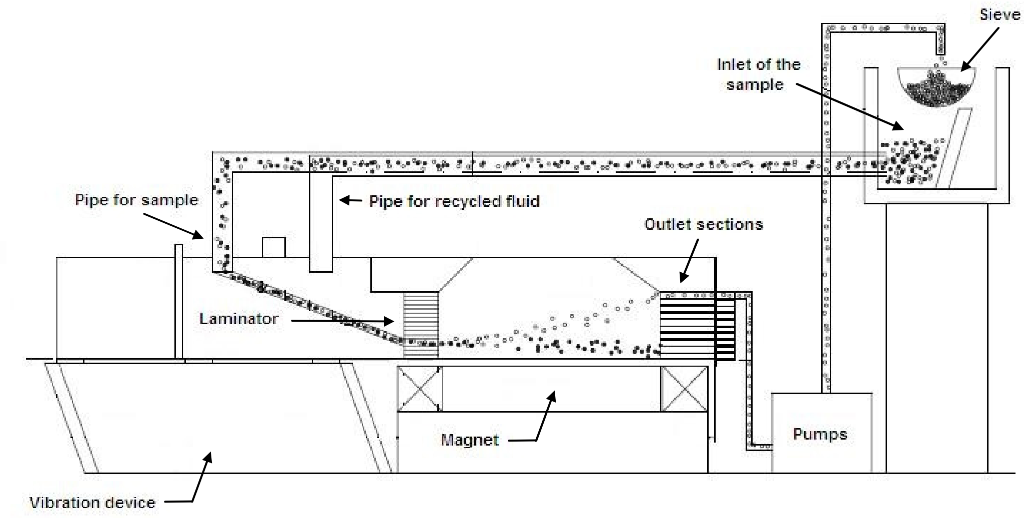


Figure 2.11 - Process of magnetic density separation: third configuration.

- The materials are fed directly into a special compartment placed under the sieve. Here they are mixed with a small quantity of magnetic liquid. Then this slurry is pumped to the magnetic density separator. The materials are sent directly into the area of separation by means of a special inlet.
- In the area of separation the materials sink or float according to their density. The separation is helped by a vibration device, which avoids materials to stick on the bottom or on the side walls of the gutter. At the end of the area of

separation the materials are divided into ten sections. Every two sections there is a pump, which pumps the material and the liquid to the sieve. Here the materials are collected, while the fluid is sent back to the separator.

- The fluid moves because of the gravity from the sieve to the separator through a pipe. This pipe is connected with the plastic lid. The laminator is cut at 50 mm: this is already sufficient to ensure a laminar flow. The resistance to the motion is reduced.
- Six new pumps are used. Five of them are used to pump the materials -already separated into different fractions- to the sieve. One is necessary to pump the slurry of sample -to be separated- and fluid into the system.

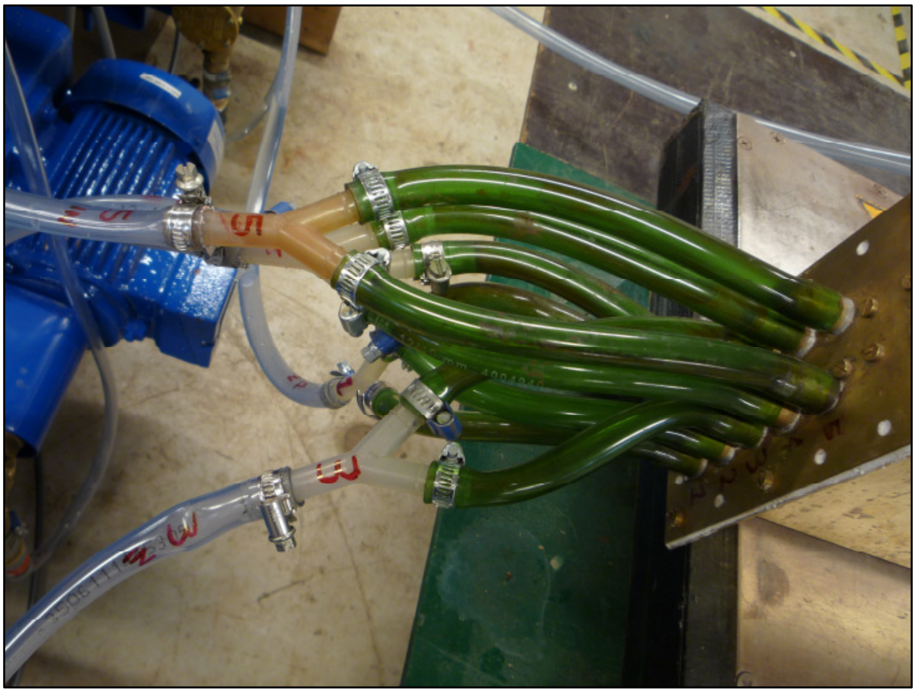


Figure 2.12 - Outlet section and connection with pumps.

The vibrating device causes only transverse vibrations to the gutter. Longitudinal vibrations could affect the separation, because they produce turbulence in the direction of the flow. Instead transversal vibrations help the separation, because avoid materials to stuck on the bottom or on the side wall of the gutter.

The vibrating device can be regulated by a controller. The vibration force can be changed and adapted to the materials that have to be separated.

In the third configuration new impeller pumps are used. They can be regulated separately.

Percentage	Hertz	Amplitude/minute
70%	35	2100
80%	40	2400
100%	50	3000

The regulation is made by a variable frequency drive (VFD). It is a system for controlling the rotational speed of an alternating current (AC) electric motor by controlling the frequency of the electrical power supplied to the motor.

Figure 2.13 - Pump with a frequency regulator.

Some tests at different frequencies have been carried out in order to investigate the relation between the flow and the frequency. The graph below shows this relation is linear. Therefore the velocity of the liquid into the pipes at different frequencies can be evaluated.

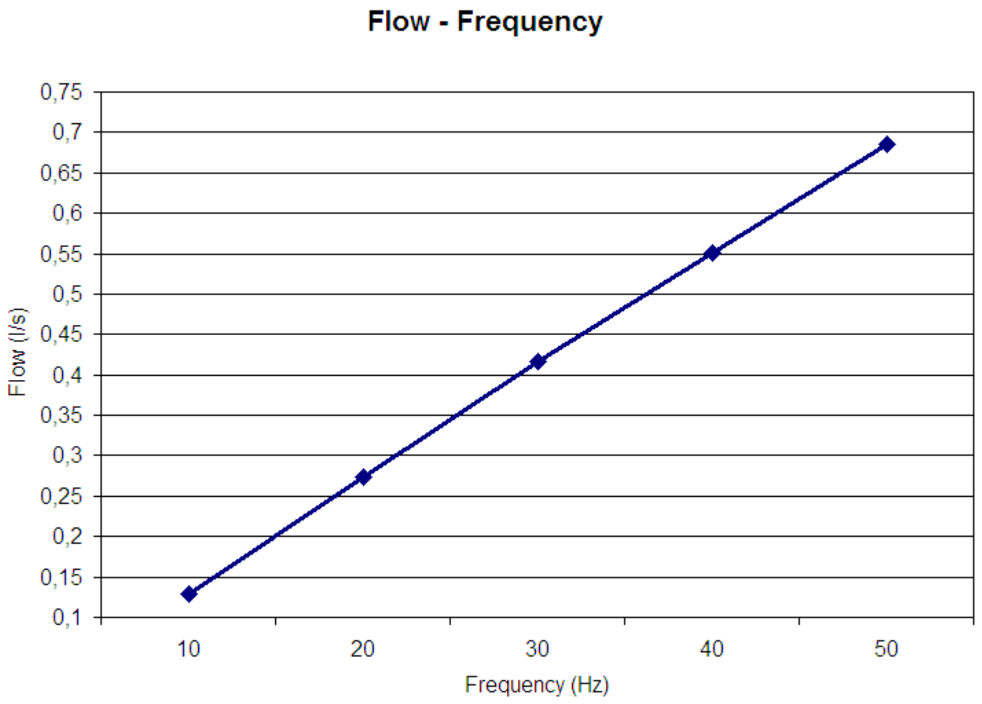


Figure 2.14 - Characterization of the pumps: relation between frequency and flow.

The pumps are connected with tubing with a diameter of 24,5 mm. By means of an adapter this tubing are then connected to a tubing with a diameter of 10 mm. In these tubing the velocity has been evaluated.

Frequency	Flow	Area	Velocity
10 Hz	0,129 l/s	0,0000785 m^2	0,164 m/s
20 Hz	0,274 l/s	0,0000785 m^2	0,349 m/s
30 Hz	0,416 l/s	0,0000785 m^2	0,530 m/s
40 Hz	0,551 l/s	0,0000785 m^2	0,702 m/s
50 Hz	0,686 l/s	0,0000785 m^2	0,873 m/s

The velocity must be high enough to transport the materials from the pumps (placed on the floor) to the sieve, which is placed 1,5 m above the floor.

To increase the velocity of the flow into the tubing, the capacity can be increased or the section of the tubing can be decreased. These pumps are very big and over measured for this gutter, so the capacity can not be increased too much. The diameter of the tubing is therefore decreased from 24,5 mm to 10 mm.

Figure 2.15 - Process of magnetic density separation: third configuration.

By this configuration the problems of turbulence and instability of the fluid level are solved. The new pumps, regulated to a low capacity, ensure a continuous flow of fluid and materials from the gutter to the sieve.

Tests with different materials, subject to different conditions, have been carried out.

Chapter 3

Experiments

3.1 First test: preparation of the equipment

For the first test different plastics have been used.

- Acrylonitrile butadiene styrene (ABS) is a common thermoplastic used to make light, rigid, molded products such as piping, musical instruments, golf club heads, automotive body parts, etc. It is a copolymer made by polymerizing styrene and acrylonitrile in the presence of polybutadiene. The particles for test were white and opaque, in the shape of small cylinders (1-2 mm).
- Polymethylmethacrylate (PMMA) is a transparent thermoplastic. Chemically, it is the synthetic polymer of methyl methacrylate. PMMA is often used as an alternative to glass, and in competition with polycarbonate (PC). It is preferred in many cases because of its moderate properties, easy handling and processing, and low cost, but behaves in a brittle manner when loaded, especially under an impact force. To produce 1 kg of PMMA, about 2 kg of petroleum is needed. PMMA ignites at 460°C and burns completely to form only carbon dioxide and water. The particles used for the test were white and transparent, in a regular shape of small cylinders (1-2 mm).
- Polyethylene terephthalate (PET) is a thermoplastic polymer resin of the polyester family, commonly used for synthetic fibers, Beverage, food and other liquid containers, thermoforming applications, and engineering resins often in combination with glass fiber. It is one of the most important raw materials used in man-made fibers. Depending on its processing and thermal history, it may exist both as a transparent and as a semi-crystalline (opaque and white) material. The particles for test were, at the beginning, white and transparent, in a regular shape of small cylinders (1-2 mm). In order to distinguish these particles from PMMA, they have been coloured with a red ink.

At the beginning other kind of plastics, like Polyoxymethylene (POM) and Polycarbonates (PC) have been taken under consideration. Unfortunately these plastics had shape and dimension that do not match with the dimension of the separator. Therefore they have not been tested.

The density is the most important parameter for the separation: the materials sink or float in a ferrofluid subject to a non-homogeneous magnetic field according to their density. Lighter materials are found in the upper sections, further from the surface of the magnet, while the heavier materials are found in the sections close to the surface of the magnet.

Figure 3.1 - Plastics used for the first test.

The density of a material (or, more accurately, the volume of a solid) can be measured through a gas pycnometer.

This device consists of a single volume chamber. The volume of the chamber can be gradually varied by means of a graduated mechanical piston. Resulting changes in pressure can be read through a transducer.

Density is merely calculated as the ratio of mass to volume, mass being invariably measured on a discrete device, usually by weighing. The volume measured in a gas pycnometer is that amount of three-dimensional space which is inaccessible to the gas (i.e. that volume within the sample chamber from which the gas is excluded). Therefore the measured volume considering the finest scale of surface roughness will depend on the atomic or molecular size of the gas. Helium is most often prescribed as the measurement gas.

Figure 3.2 - Gas pycnometer.

Material	Chemical Formula	Experimental Density	Colour
ABS	$(C_8H_8C_4H_6C_3H_3N)_n$	1053,313 kg/m^3	Opaque white
PMMA	$(C_5O_2H_8)_n$	1215,479 kg/m^3	Transparent white
PET	$(C_{10}H_8O_4)_n$	1351,252 kg/m^3	Red

3.1.1 The magnetic fluid

The fluid for the experiments originates from Ferrotec and is a stable colloidal suspension of magnetic particles in water. The magnetic particles are coated with a surfactant which prevents the particles to agglomerate, even when the fluid is placed in a strong magnetic field gradient.

A magnetization M=18000 A/m and a density ρ_f =1,156 kg/m^3 have been measured for the pure fluid. The magnetic fluid can be diluted using water in order to create a suitable density range for the separation. The dilution of the fluid affects the height at which the particles float, but the distance among particles with different density does not change. Particularly, the dilution influences the magnetization M and density ρ_f of the fluid: M changes linearly with the dilution factor and ρ_f can be recalculated since the densities of water and pure fluid are known.

About determination of dilution factor, it is important that particles that have to be extracted from the mixture should not end up in the lower part of the magnetic field, where there are low density trenches. About 60 litres of fluid, into three buckets of 20 litres each one, are supposed to be necessary for the preparation of the magnetic fluid with the optimal dilution. With 0,66 litres of pure magnetic fluid and 19,33 litres of water in each bucket, a fluid with a dilution factor of 1:30 is thus prepared.

The magnetization and the density should be measured.

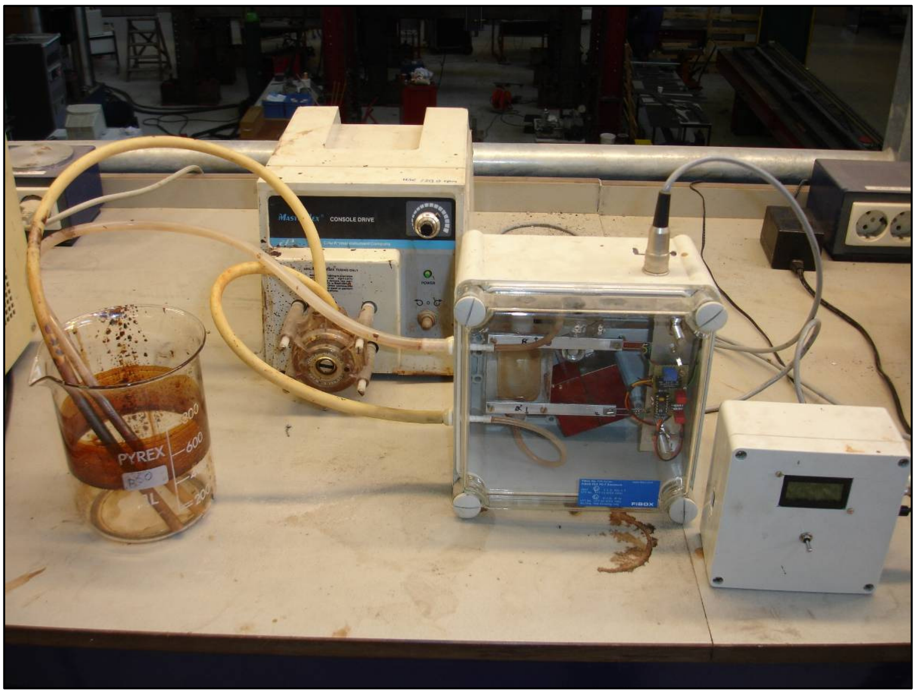


Figure 3.3 - Equipment to measure the magnetization of the fluid.

The magnetic fluid is collected in a glass and pumped to a small transparent plastic bag inside a box. The bag is connected by means of two metallic stripes to a system that measures their displacement. The angular displacement of the stripes is caused by the attraction between the magnetic fluid (inside bag) and a red magnet that rotates behind the bag. The displacement is proportional to the magnetization of the fluid: a strong displacement means a strong magnetization.

This equipment can measure the magnetization of a magnetic fluid with a dilution factor ≤ 1:10 (M<3000 A/m). With a higher magnetization the displacement is so high that the transparent bag touches the magnet and the measurement is not reliable.

A hydrometer is required for measuring the density of a magnetic fluid. It is an instrument used to measure the relative density of a liquid (ratio of the density of the liquid to the density of water).

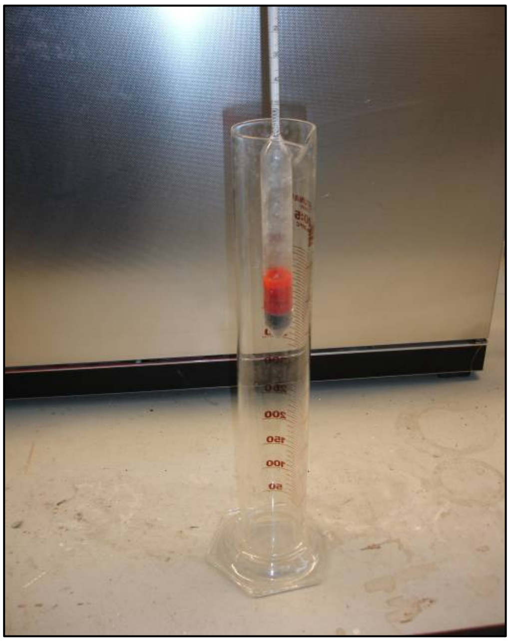


Figure 3.4 - Hydrometer.

A hydrometer is usually made of glass and consists of a cylindrical stem and a bulb weighted with mercury or lead shot to make it float upright. The liquid to be tested is poured into a tall jar, and the hydrometer is gently lowered into the liquid until it floats freely. The point at which the surface of the liquid touches the stem of the hydrometer is noted. Hydrometers usually contain a paper scale inside the stem, so that the specific gravity can be read directly. The operation of the hydrometer is based on the Archimedes principle that a solid suspended in a liquid will be buoyed up by a force equal to the weight of the liquid displaced. Thus, the lower the density of the substance, the lower the hydrometer will sink.

The magnetization and the density measured for each bucket of fluid are reported in the following table.

Bucket	Magnetization	Density
1	601 A/m	1004 kg/m^3
2	609 A/m	1004 kg/m^3
3	614 A/m	1004 kg/m^3

3.1.2 Sink-float tests

Figure 3.5 shows the position of the magnet under the separator. The flow is through X axis, while Y axis represents the width of the gutter. Z axis indicates the height from the surface of the magnet.

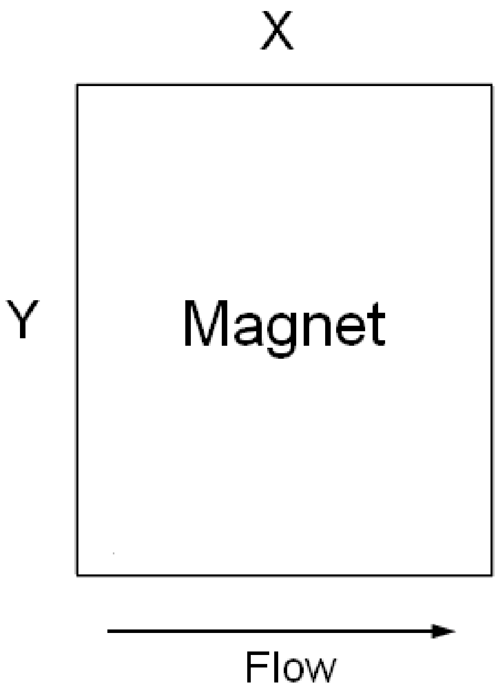


Figure 3.5 - Direction of the flow above the magnet.

Figure 3.6 shows the theoretic density profile by using a dilution factor of 1:30, consisting in one part of magnetic fluid mixed with twenty-nine parts of water.
X axis represents the direction of the flow. At the beginning (x = 0 mm) and at the end (x = 48 mm) of the magnet the density is lower than in the central area. The

area of separation spreads from 100 mm to 400 mm. In this range the density of the fluid is constant (along X axis).

Z axis represents the height from the surface of the magnet. The density grows with z coordinate following an exponential progress. For z < 27 mm the trend of the density is characterized by low density trenches. If the materials are trapped in these trenches, they can not be separated into correct fractions.

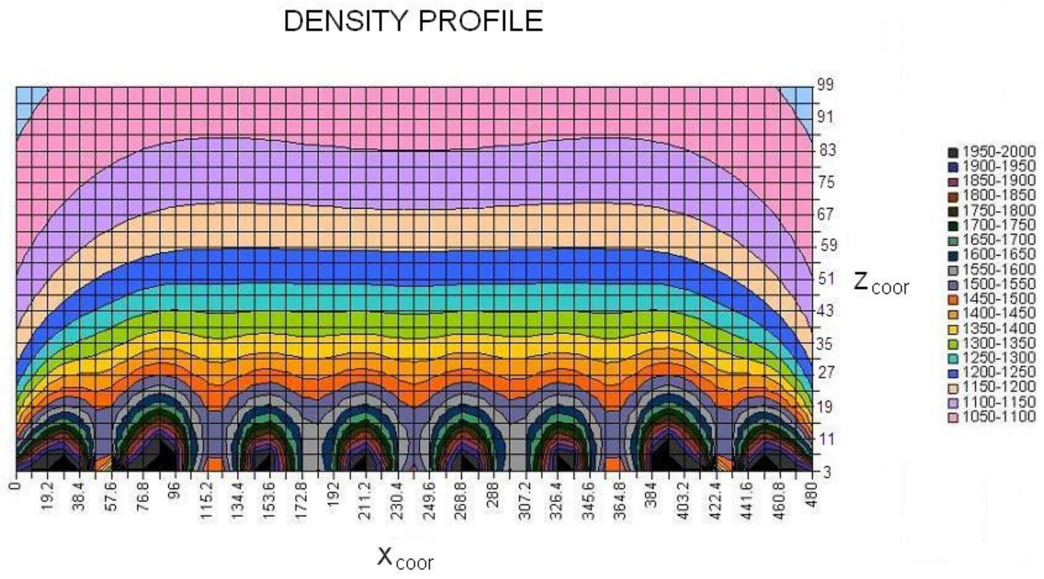


Figure 3.6 - Density profile in a ferrofluid with a dilution 1:30 and a magnetization of 600 A/m.

According to this profile it is possible to suppose the floating height of each material depending on its density.

The floating height is calculated from the surface of the magnet. The separator is placed 4 mm above the magnet surface. The outlet is divided in 5 sections and the height of each one is 20 mm.

Material	**Theoretical Floating Height (from surface of the magnet)**	**Section of outlet**
PET	15 ÷ 27 mm	1 - 2
PMMA	39 ÷ 47 mm	2 - 3
ABS	75 ÷ 95 mm	4 - 5

PET is supposed to float between 15 mm and 27 mm from the surface of the magnet. In this range it is canalized into the first and the second section (from the bottom of the gutter). PMMA should be found into the second and the third section. ABS is the lighter material: it is supposed to float on the higher layer, in relation with the fourth and fifth section.

Some sink-float tests have been carried out in order to evaluate the height of each material in a magnetic fluid column. On the basis of results, it is possible to know if the theoretic floating heights match with experimental floating heights.

Particles of material are added to a glass filled with a certain quantity of magnetic fluid with dilution factor of 1:30 (particles have been previously wetted by a steam jet in order to prevent the generation of air bubbles at the surface). At this phase the particles settle on the bottom of the glass. By placing the glass onto a magnet the particles start to float on the surface of the fluid, due to his high apparent density. Small quantities of fluid are gradually added and the particles continue floating until the apparent density of the fluid is higher than the density of the material. When the apparent density of the fluid becomes the same of material, the particles disappear from the surface and remain just beneath the level of the fluid, which represents the floating height of the material.

The following table shows the results of the experimental sink float tests.

Material	**Experimental Floating Height (from surface of the magnet)**	**Section of outlet**
PET	20 ÷ 30 mm	1 - 2
PMMA	35 ÷ 50 mm	2 - 3
ABS	100 ÷ 110 mm	5

PET is separated into section 1 and 2, as supposed with theoretic analysis, while PMMA is separated into section 2 and 3. About ABS, the floating height resulted from experimental test is higher then the theoretic one.

3.1.3 Time of separation

With reference to a magnetic fluid with a dilution factor of 1:30, the time required from the particles to reach their floating height has been evaluated.

The particles are fed within a range between 20 mm and 30 mm (from the bottom of the gutter), although a medium height of 25 mm has been studied. Graph below (Figure 3.7) shows as PET and PMMA particles need only 0,45 seconds to reach their floating heights; differently, a particle of ABS needs 2,45 seconds to reach its position of equilibrium.

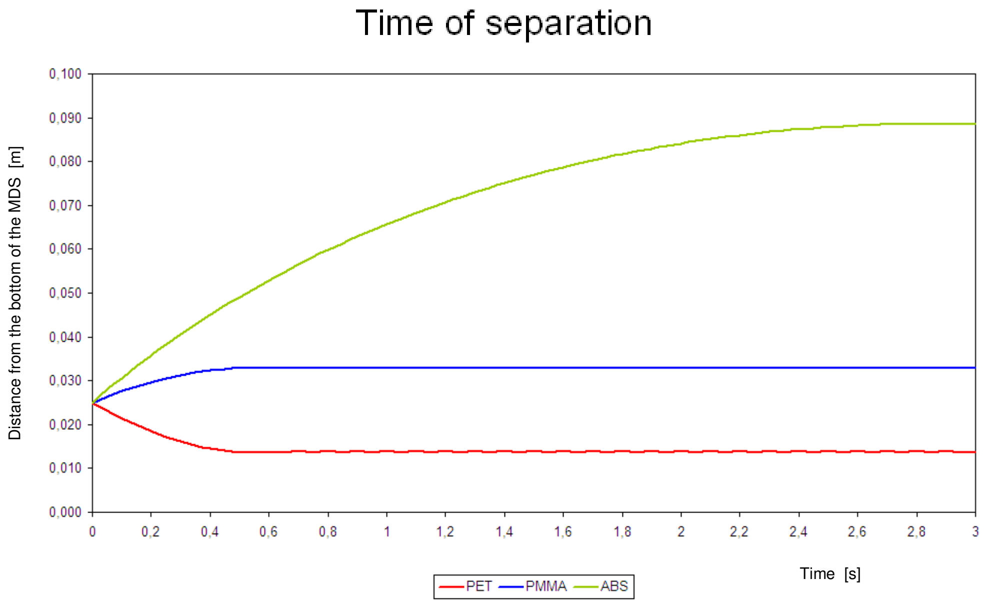


Figure 3.7 - Time for plastic particles to reach the theoretical floating height.

3.2 The Experiments

The aim of these experiments has been the separation of different kind of plastic, as well as the investigation of all parameters able to affect the separation itself. In each test only one parameter has been changed, while the others have been kept stable.

3.2.1 Wetting

The wetting is an important process that avoids air bubbles to cling the surface of the materials. When air bubbles cling to the surface of the materials, the density of the materials decreases and the materials start floating towards a different position as regards to the expected floating height.

It is very important to wet the materials before putting them into the system. Different attempts have been made to find the best process. The materials are wetted using a steam jet. In a closed case full of water an electric resistance heats the water. When the water starts boiling, the steam goes out from a hose.

At the first attempt, some samples of materials are placed on a circular sieve. Then they are wetted by a steam jet in all directions. After 30 seconds the samples are thrown in a glass full of water, in order to prevent the contact with air. Finally the samples are subjected to the magnetic density separation.

This wetting process is the best one, although some problems can occur: because of the transfer from different containers, the materials are subjected to different temperatures and air bubbles can form. In order to avoid these multiple steps, the particles are wetted directly inside a glass: when the steam is in touch with the glass, it condenses around the particles and creates a layer of hot water. Afterwards the material is fed inside the system. In this way the process is faster and the risk of air bubbles at the surface of particles is very low.

The first test has been carried out without the wetting of the materials: the materials are fed directly into the system. The second test has been carried out with wetted materials.

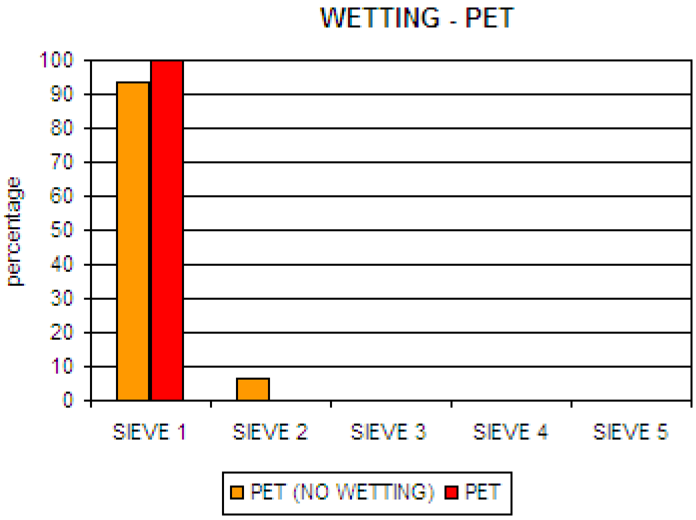


Figure 3.8 - Test results for PET material: wetted particles and no-wetted particles.

Other parameters have been kept stable: the sample weight 10 grams, the frequency of each pump is 10 Hz, the materials are fed separately in order to avoid interaction between different materials, the sections of outlet are placed 4 mm above the surface of the magnet.

Fig. 3.8 shows the results for PET material. When PET is wetted, it ends up only in the first section at the bottom of the gutter. When PET is not wetted, a small quantity is found into the second sieve too: this is the effect of air bubbles that cling to the surface of the material.

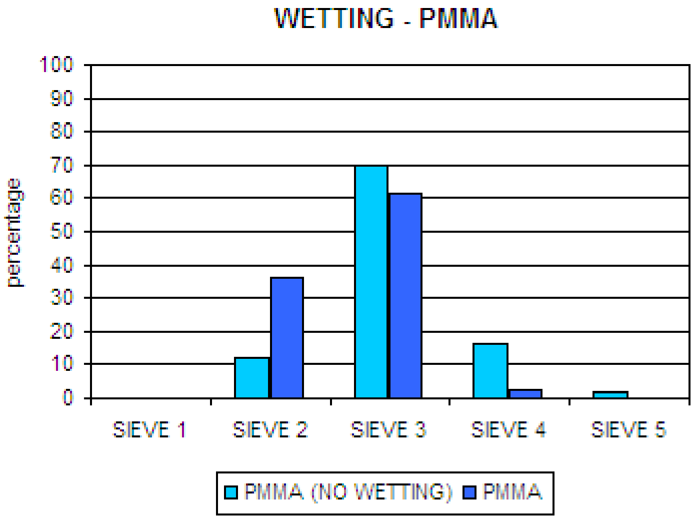


Figure 3.9 - Test results for PMMA material: wetted particles and no-wetted particles.

The effect of air bubbles is visible for PMMA too (Fig. 3.9). When PMMA is not wetted, the separation concerns the last four sieves. PMMA is found mainly in the third sieve, but considerable quantities of material are found also in sieves 2 and 4. A small quantity of material is found in sieve 5. Air bubbles cling to the surface and the particles start floating by ending up in different levels. When PMMA is wetted, the separation concerns mainly the second and third sieve, while only a small amount of material is found in sieve 4. The fifth sieve is empty. In this last case, it is interesting to point out that materials tend to float at a lower height. Besides there are no air bubbles and the particles separates according to their real density.

Differently, the wetting does not influence the separation of ABS (Fig. 3.10). In fact air bubbles let the materials float in a higher level, while ABS floats already on the surface of the fluid.

Definitively, wetting is an important factor because affects the separation, especially for those materials that float into intermediate levels (middle of the fluid).

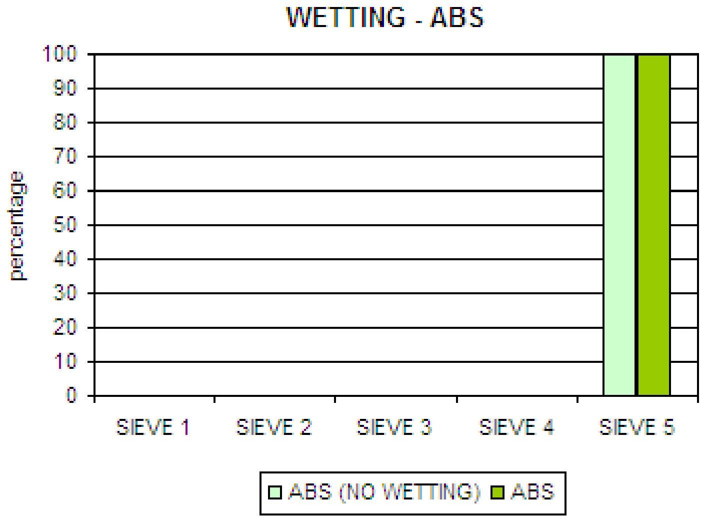


Figure 3.10 - Test results for ABS material: wetted particles and no-wetted particles.

3.2.2 Frequency

By changing the frequency of the pumps it is possible to modify the velocity of the flow. Unfortunately the pumps chosen for this system were over measured, therefore it has been compulsory to work at a low frequency. The relation between the frequency and the flow is linear. In other words, if the pump works at 20% of its maximum frequency, the velocity is 20% of its maximum value too.

In this test the frequency has been changed in order to see if this parameter influences the separation.

The particles (samples of 10 grams) are wetted, and then separately fed. The sections of outlet are placed 4 mm above the surface of the magnet.

One big problem is to prevent the generation of air bubbles, not only at the surface of the materials, but also inside the whole system. Air bubbles inside system might trap the materials and counterfeit the separation.

When all pumps are set to 10 Hz, no bubbles are found inside system and the level of the liquid is nearly stable.

All PET ends up in the first sieve, as expected by the sink-float test (Fig. 3.11).

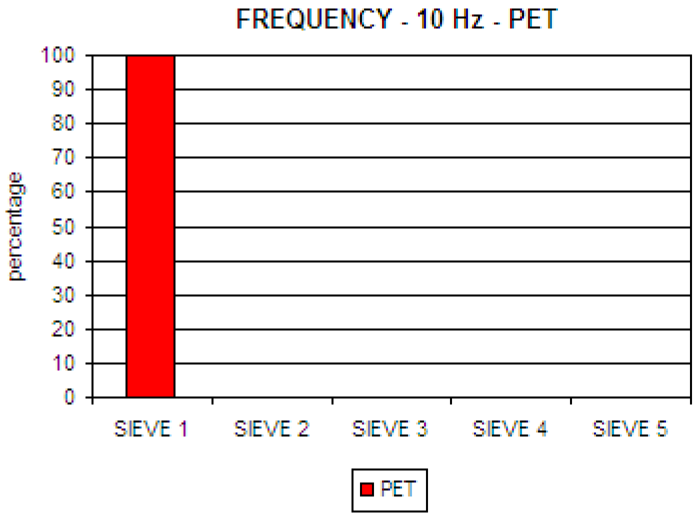


Figure 3.11 - Test results for PET material (wetted particles) when the pump is set to 10 Hz.

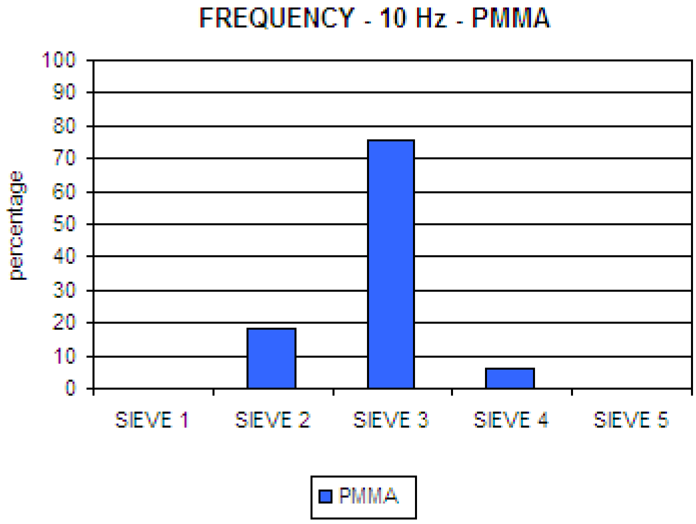


Figure 3.12 - Test results for PMMA material (wetted particles) when the pump is set to 10 Hz.

PMMA is mainly found into sieves 2 and 3, although a small amount of material is found in sieve 4 too (probably there are still air bubbles clung to the surface), as shown in Fig. 3.12.

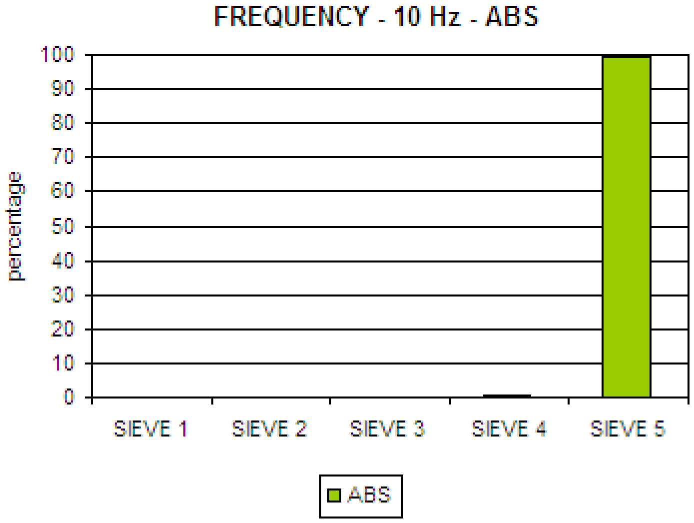


Figure 3.13 - Test results for ABS material (wetted particles) when the pump is set to 10 Hz.

ABS ends up mainly in sieve 5 (Fig. 3.13). A very small percentage (0,69%) is found in sieve 4: probably the particles can not reach the highest section because they are obstructed by other particles.

Air is found inside system when are set to a frequency of 11 Hz. Particularly, pump 5 swallows air and causes foam over the sieve. Foam is also seen on the surface of the fluid (inside separator).

All PET ends up in sieve 1, as shown in Fig. 3.14: the change on velocity does not affect his behaviour. PMMA is mostly found in compartment 2 and 3 (Fig. 3.15). It is experienced a bigger quantity of PMMA in sieve 2, while the quantity in sieve 3 is lower. Small quantities are found in sieves 1 and 4. Therefore the increase on velocity affects the behaviour of this material. The particles spread among four sieves, within a range of 800 mm. Probably the velocity is too high and the materials can not reach their own floating height, although it has been theoretically calculated that in a stationary system a particle of PMMA needs only 0,45 seconds to reach his floating position. It might be also possible that the increase on velocity causes the turbulence of the flow and in the same way the particles do not reach and keep the floating height.

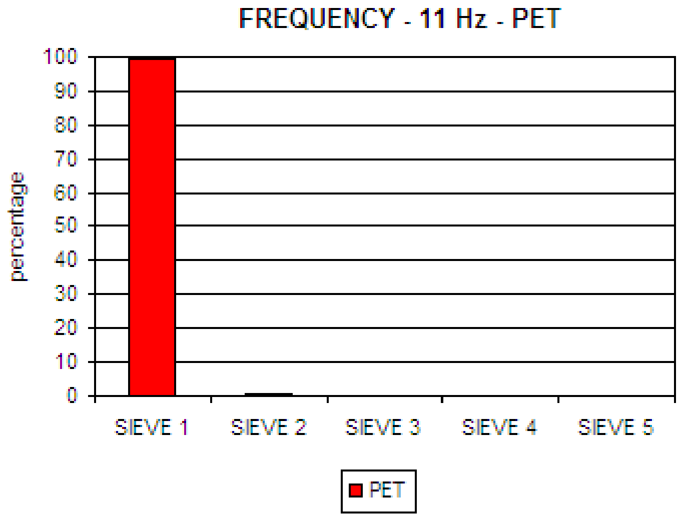


Figure 3.14 - Test results for PET material (wetted particles) when the pump is set to 11 Hz.

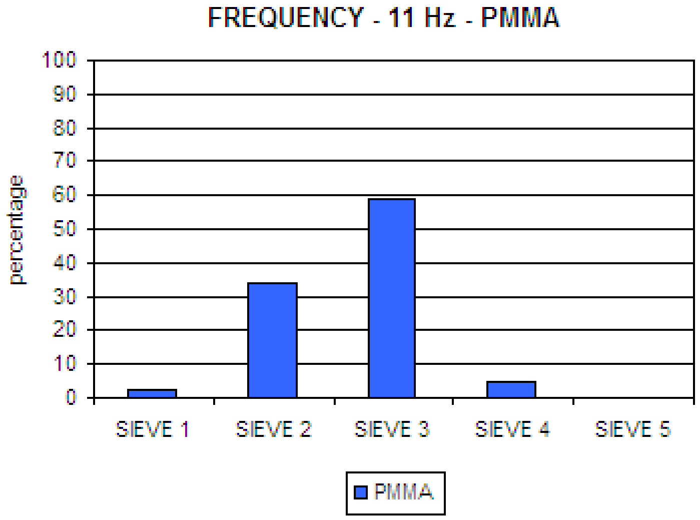


Figure 3.15 - Test results for PMMA material (wetted particles) when the pump is set to 11 Hz.

All ABS is found in sieve 5 (Fig. 3.16). Although pump 5 swallows air, the change of velocity does not influence the behaviour of this material, so that means the intermittent working (air and fluid) of the pump during the process. The test also shows a blockage between the pump and the tubes: the materials are stopped in the connection between pump's outlet and tubes (d = 10mm). This connection is the weak point of the system because the section decreases suddenly: the materials must be poured very slowly to avoid any risk of blockage.

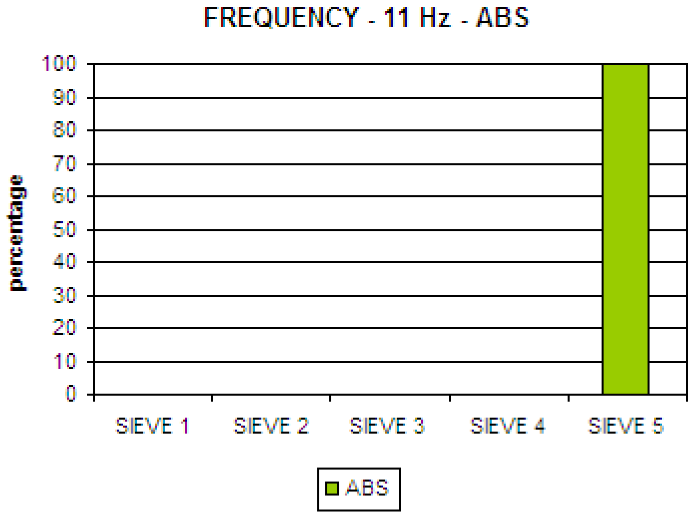


Figure 3.16 - Test results for ABS material (wetted particles) when the pump is set to 11 Hz.

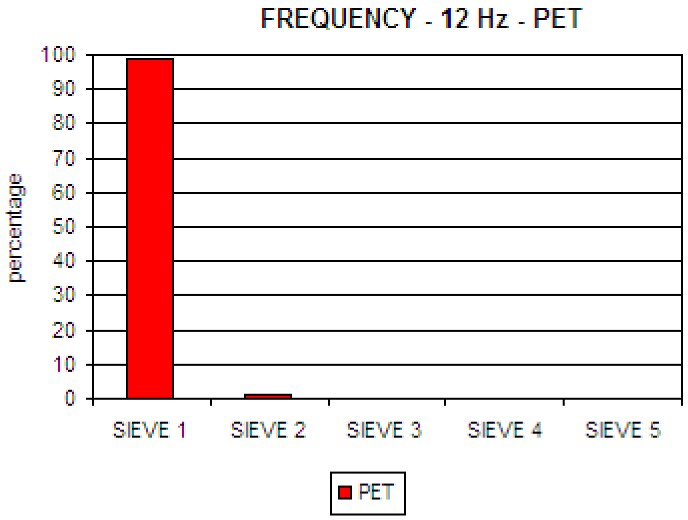


Figure 3.17 - Test results for PET material (wetted particles) when the pump is set to 12 Hz.

When all pumps are set to a frequency of 12 Hz the velocity is too high for the separation: there are many air bubbles inside the system and the flow is turbulent. A small quantity of PET is found in sieve 2 (Fig. 3.17). PMMA is mostly found in sieve 2 and 3; a small quantity is found in sieve 1 and 4 too (Fig. 3.18). ABS is found in sieve 5, while only a small quantity concerns the sieve 4 (Fig. 3.19). Because of turbulence of the system (resulting from the high velocity), in this last test the separation of the materials are less accurate than in the other tests.

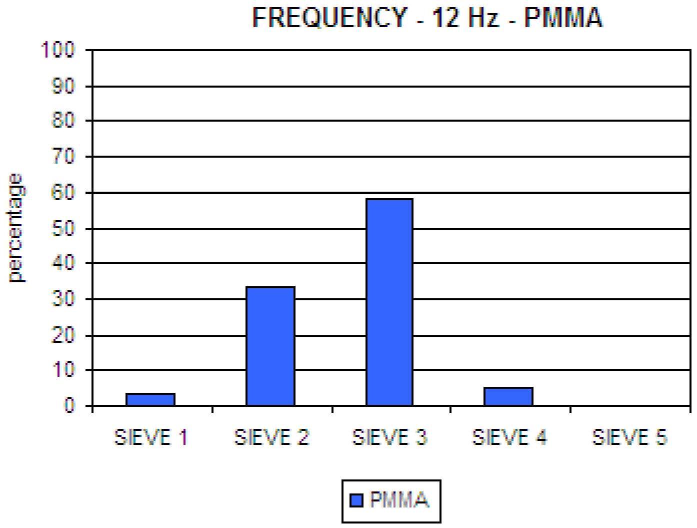


Figure 3.18 - Test results for PMMA material (wetted particles) when the pump is set to 12 Hz.

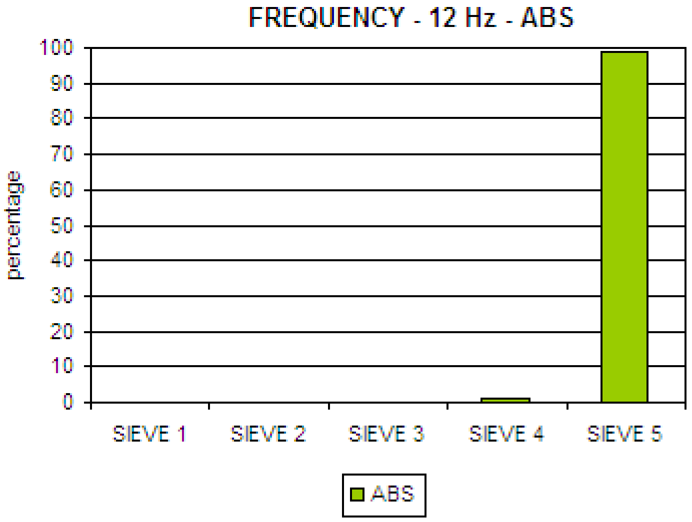


Figure 3.19 - Test results for ABS material (wetted particles) when the pump is set to 12 Hz.

3.2.3 Interaction among particles of the same materials

The aim of this test has been the study of the interaction amongst particles of same materials. Particularly the method of feeding has been investigated. The particles are fed one by one in the first test and all in once in the second test in order to see what change during process of separation. This test has been carried out only with PMMA because the separation of this material is not so accurate like the others.

Following graphs show the results about tests with particles of PMMA with different weight (2, 5 and 10 grams).

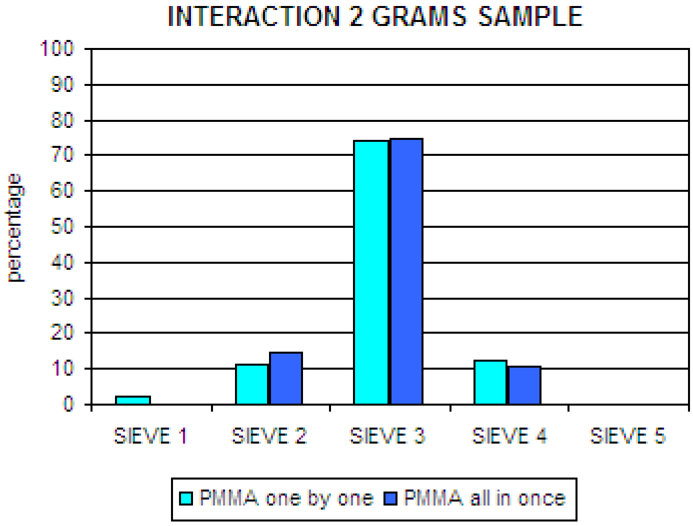


Figure 3.20 - Test results for PMMA sample of 2 grams: comparison between feeding one by one and feeding all in one.

About particles of 2 grams, the results (Fig. 3.20) are nearly the same for both of tests: the samples are so small, that there is almost no difference between feeding the particles one by one and feeding them all in once. Nevertheless it is possible to infer that if the particles are fed one by one the separation is slightly more precise.

Most particles of 5 grams are found in sieve 3 (Fig. 3.21), while small quantities are found in sieve 2 and 4 (with the same percentage of samples of 2 grams). When the particles are fed all in once, the percentage in sieve 3 decreases and the percentage in sieve 4 increases. Probably when the particles are fed all in once they group together, therefore they can not reach the correct section.

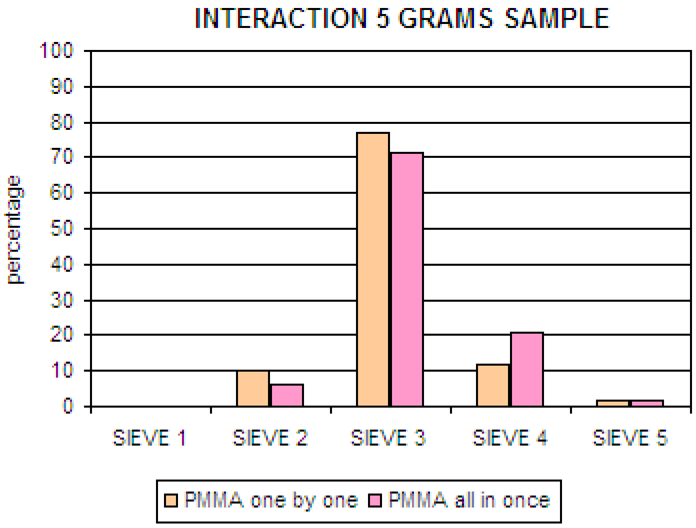


Figure 3.21 - Test results for PMMA sample of 5 grams: comparison between feeding one by one and feeding all in one.

Particles of 10 grams fed one by one are mostly found in sieve 3, while 30% of them are found in sieve 2 and a small quantity in sieve 4 (Fig. 3.22). Few particles are found in sieve 5. These particles become cold because the process requires time; probably they have small air bubbles on the surface, so they float.

The system goes out of use when the particles are fed all in once: they clog the connection between the pump and the tubing. The separation is not accurate. Due to the blockage of pump 3, many particles are found in sieve 4.

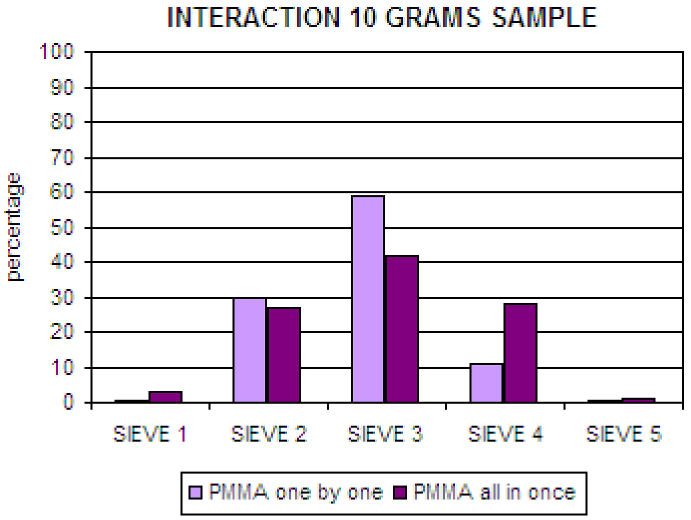


Figure 3.22 - Test results for PMMA sample of 10 grams: comparison between feeding one by one and feeding all in one.

3.2.4 Interaction among different materials

The aim of the test has been the study of the interaction amongst different materials in order to investigate if a group of particles can influence the motion of other particles. The particles are fed through a vibrating feeder in order to prevent any clog inside system.

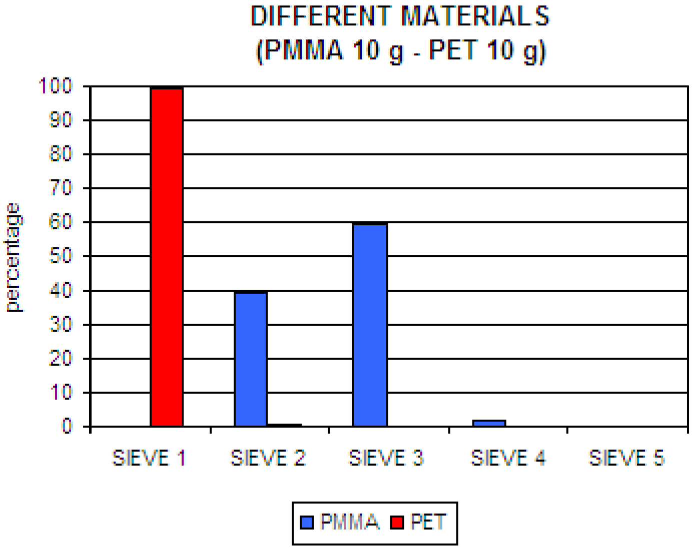


Figure 3.23 - Test results about interaction between two materials: PMMA sample of 10 grams and PET sample of 10 grams.

Two different materials are fed together in a same quantity (Fig. 3.23). All PET particles reach the sieve 1, although a very small percentage is found in sieve 2. The behaviour of PET does not seem to be influenced from the presence of PMMA. PMMA is mostly found in sieve 3. Only a small amount is found in sieve 4. The quantity of PMMA found in sieve 2 is higher than that found during basic test: probably PET traps some particles of PMMA and drags them towards a lower level.

The behaviour of PET does not change when particles of 20 grams have been tested (Fig. 3.24): the most quantity is found in the first section, while a small quantity is found in sieve 2. In a different way, PMMA is mainly found in sieve 2 (usually its separation concerns the sieve 3). Therefore big quantities of PET can influence the PMMA behaviour: the latter can not reach its floating height.

Through the last test (Fig. 3.25) it has been experienced that a bigger quantity of PMMA does not affect the behaviour of PET.

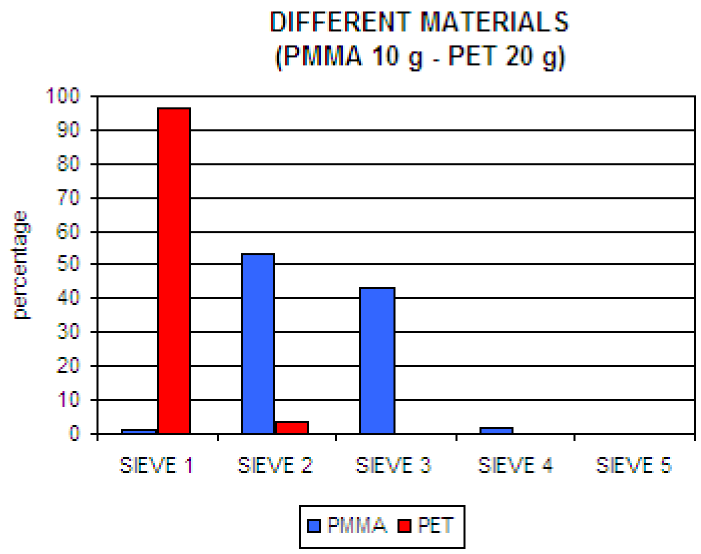


Figure 3.24 - Test results about interaction between two materials: PMMA sample of 10 grams and PET sample of 20 grams.

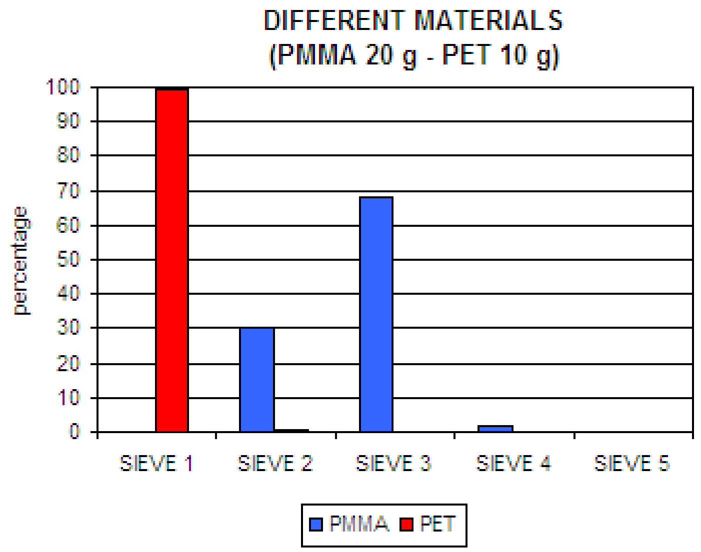


Figure 3.25 - Test results about interaction between two materials: PMMA sample of 20 grams and PET sample of 10 grams.

3.2.5 Height of the gutter

Further tests with gutter at different heights have been performed in order to find if it is possible to carry all PMMA particles in one sieve.

The results of the first test refer to a gutter placed 10 mm above the magnet. Due to the weight of the tubing in connection with the outlet, the sections for separation are only 4 mm above the magnet (Fig. 3.26). By this configuration the PMMA is mostly found in sieve 3. PMMA is not found either in sieve 1 or in sieve 5. The separation is quite good.

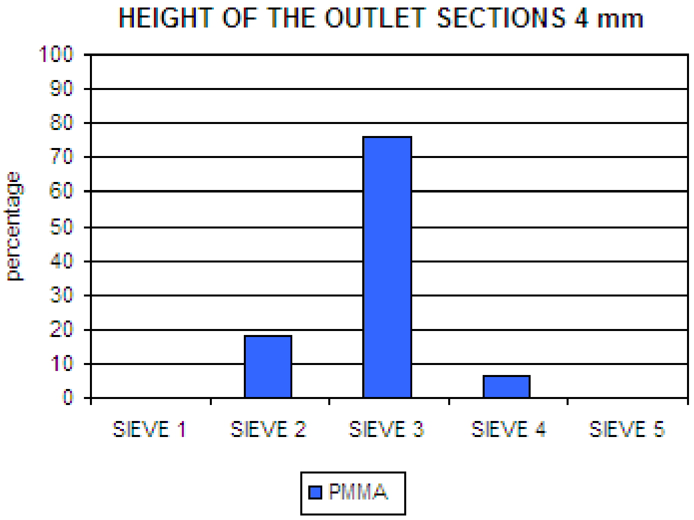


Figure 3.26 - Test results for PMMA material when outlet sections are 4 mm above the magnet.

When the outlet sections are 11 mm above the magnet, the PMMA is found in sieve 2 and 3 in a percentage of 45% and 37% respectively (Fig. 3.27). Unfortunately some particles are found in sieve 5 too, probably because of an inaccurate wetting of the particles.

If the outlet sections are 14 mm above the magnet (Fig. 3.28), most PMMA particles are found in sieve 2 (63%). A percentage of 28% is found in sieve 3, while only a small percentage is found in sieve 1 and 4. The separation is then quite good, but the material is still split into 4 different sections.

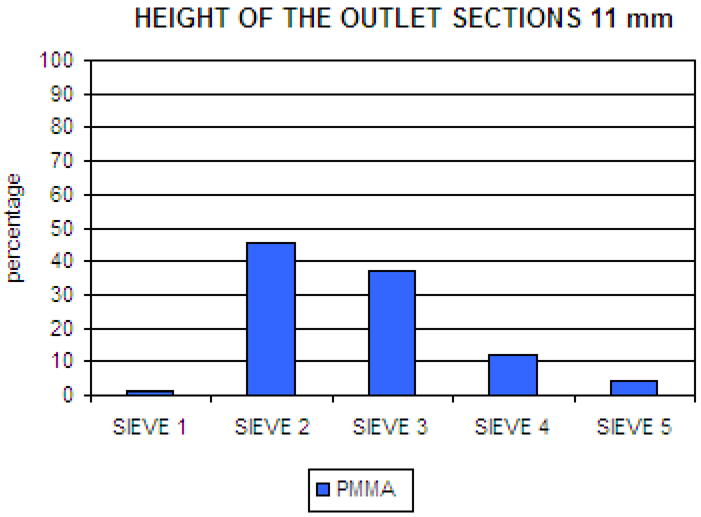


Figure 3.27 - Test results for PMMA material when outlet sections are 11 mm above the magnet.

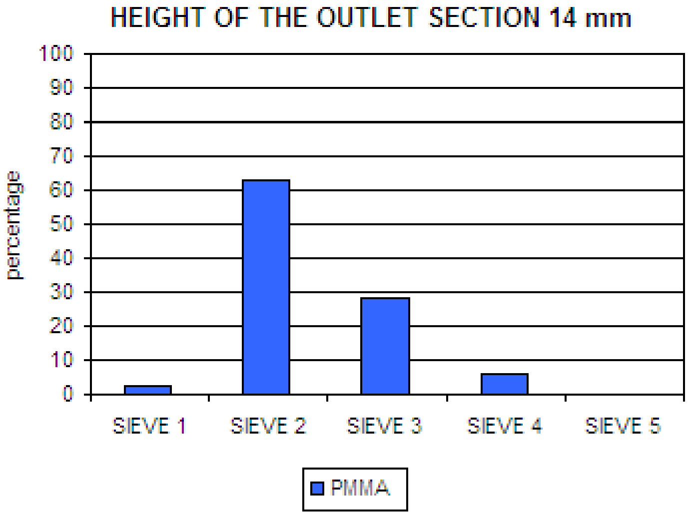


Figure 3.28 - Test results for PMMA material when outlet sections are 14 mm above the magnet.

The last configuration with 18 mm of height (Fig. 3.29) has not shown the expected results. Most of PMMA is found in sieve 2 (60%) but a high percentage of this material is found in sieve 1 (16%) too. This separation is not good.

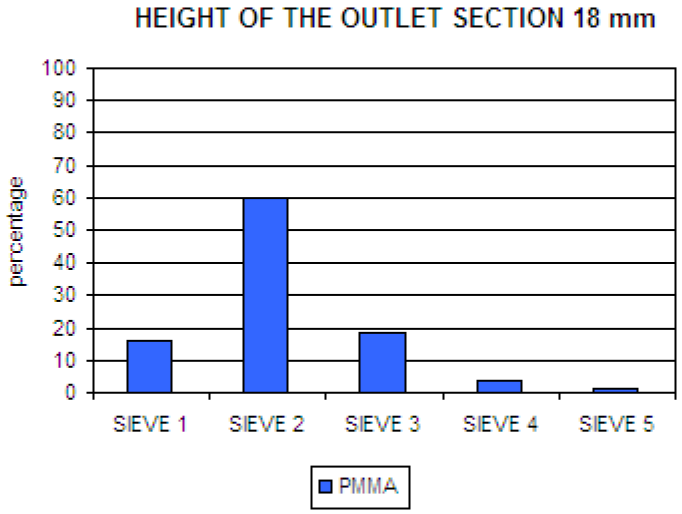


Figure 3.29 - Test results for PMMA material when outlet sections are 18 mm above the magnet.

3.2.6 Final Test

After analysis of all parameters, a final test has been carried out by setting the system with the best conditions (Fig. 3.30):

- Wetting: it is really important to wet the particles in order to prevent the generation of air bubbles at the surface of the particles. Particles with air bubbles end up in a wrong level of separation.
- Frequency: PET and ABS are not affected by changes in frequency, as well as in the flow and velocity of the system, but PMMA does. It is important to keep the velocity slow: particles with turbulence end up in a wrong level of separation.
- Vibrating feeder: in order to prevent the interaction amongst the particles it is really important to feed them in a stable and slow way through a vibrating feeder. An optimal separation can be achieved when samples of different materials are in the same quantity.
- Height of the gutter: the configuration with outlet sections placed 4 mm above the magnet ensures the best separation of PET and ABS, as well as of PMMA (mostly found in sieve 3).

- Capacity of the system: samples over 30 grams can not be tested in order to prevent any clogs inside system.

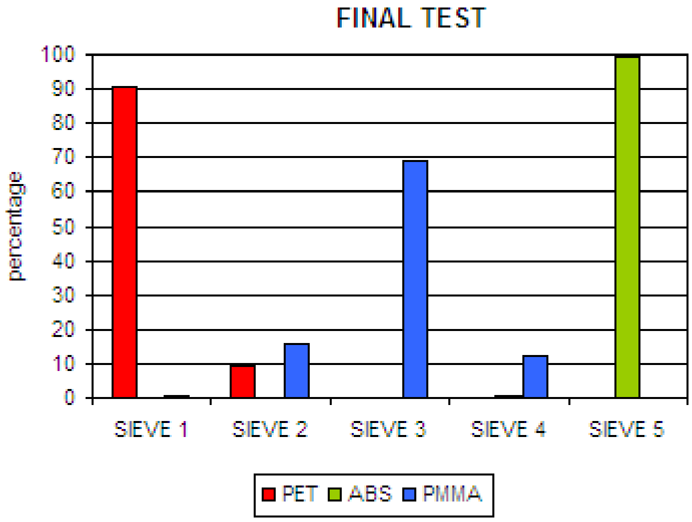


Figure 3.30 - Test results about interaction among all materials under the best operative conditions.

The final test shows the separation among different kind of plastic (with densities very similar to each other) is possible and gives good results.

All PET is found in the first sieve, while only a small quantity is found in the higher section. The best results are achieved with ABS: all material is found in the sieve 5.

Test on PMMA shows some problems. The separation is not so accurate like other materials because each parameter influences the process. Therefore it is not possible to find a method able to collect all PMMA in one sieve.

3.3 Second test: preparation of the equipment

In these tests copper, aluminium and a mixed plastic/stone/glass/copper fraction are tested.

- Copper is a chemical element with the symbol Cu and atomic number 29. It is a ductile metal with a very high thermal and electrical conductivity. Copper is rather supple in its pure state and (when fresh) has a pinkish or peachy colour, which (besides gold) is unusual for metals, which are usually silvery or grayish. It is used as a thermal conductor, an electrical conductor, a building material, and a constituent of various metal alloys. The material is milled in a spherical shape with particles of 1 mm of diameter.

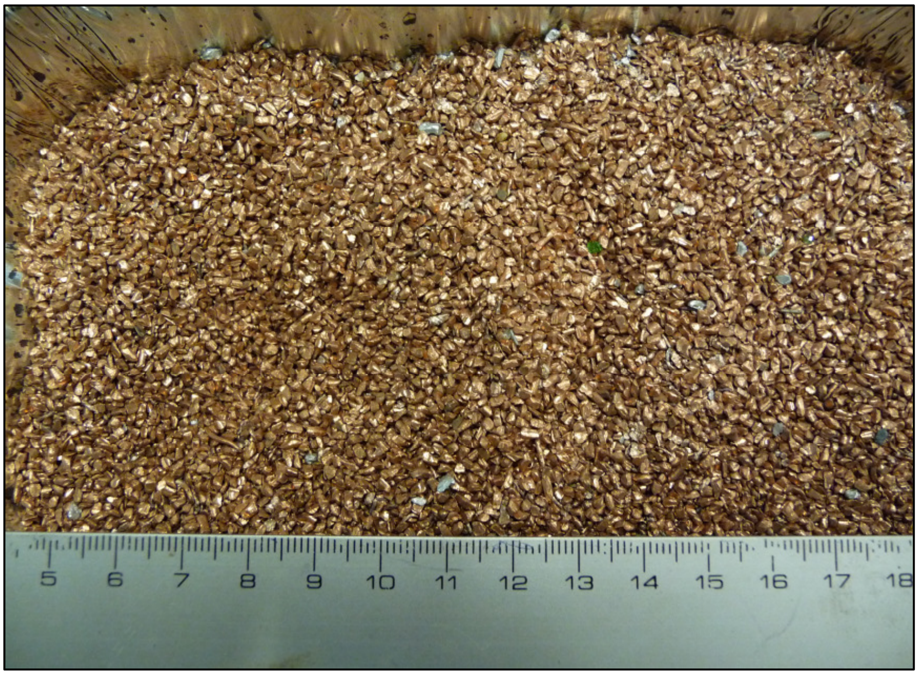


Figure 3.31 - Copper.

- Aluminium is a silvery white and ductile member of the boron group of chemical elements. It has the symbol Al and its atomic number is 13. It is not soluble in water under normal circumstances. Aluminium is the most abundant metal in the Earth's crust, and the third most abundant element therein, after oxygen and silicon (it makes up about 8% by weight of the Earth’s solid surface). Aluminium is too reactive chemically to occur in nature as the free metal. Instead, it is found combined in over 270 different minerals. The chief source of aluminium is bauxite ore. Aluminium is remarkable for its ability to resist corrosion (due to the phenomenon of passivation) and its low density. Structural components made from aluminium and its alloys are vital to the aerospace industry and very important in other areas of transportation and building. Its reactive nature makes it useful as a catalyst or additive in chemical mixtures, including being used in ammonium nitrate explosives to enhance blast power. The material is milled in a spherical shape with particles of 1 mm of diameter.

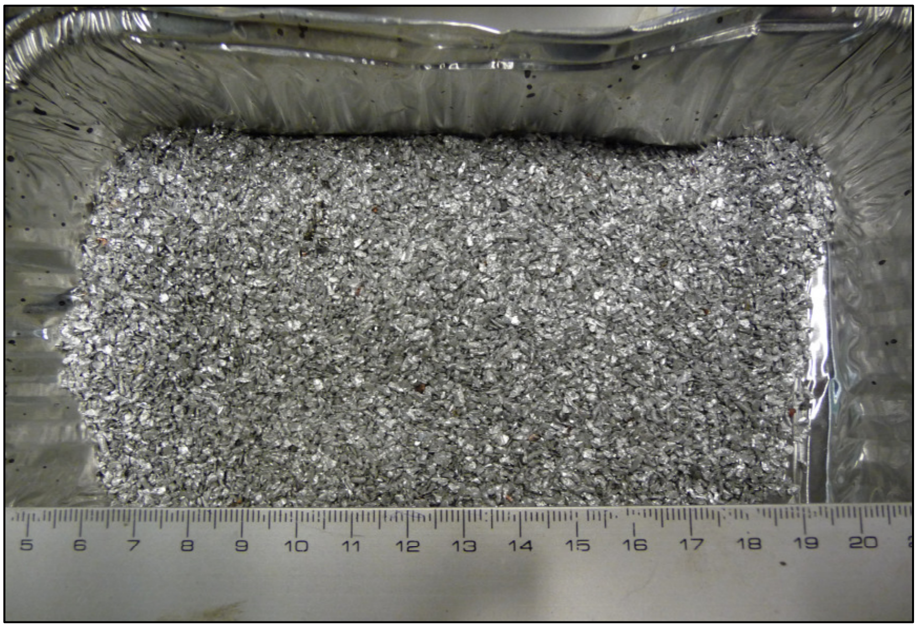


Figure 3.32 - Aluminium.

- A combination of plastic/stone/glass/copper[1] derived from WEEE (Waste Electrical and Electronic Equipment). The copper fraction is present in form of tiny wires. The mixture is mainly formed by polyvinylchloride (PVC), the third most widely used thermoplastic polymer after polyethylene and polypropylene. In terms of revenue generated, it is one of the most valuable products of the chemical industry. Around the world, over 50% of PVC manufactured is used in construction (the PVC world market grew with an average rate of approximately 5% in the last years and will probably reach a volume of 40 million tons by the year 2016). As a building material, PVC is cheap, durable, and easy to assemble. It can be made softer and more flexible by the addition of plasticizers, the most widely-used being phthalates. In this form, it is used in clothing and upholstery, and to make flexible hoses and tubing, flooring, to roofing membranes, and electrical cable insulation. It is

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[1] This combination of different materials has been provided by Axion Polymers. This Company has been created to produce high grade polymer compounds for re-use in new products and equipment. Available in different grade depending on the specification required, these polymers are designed for a wide range of applications such as computer, electrical, electronic and automotive components. Axion Polymers has built one of the most advanced plastics recycling factories in Europe to separate and compound recycled plastics initially from Waste Electrical and Electronic Equipment (WEEE), with the potential to develop recycling routes for additional plastics from other sources.

also commonly used in figurines and in inflatable products such as waterbeds, pool toys or jump houses.

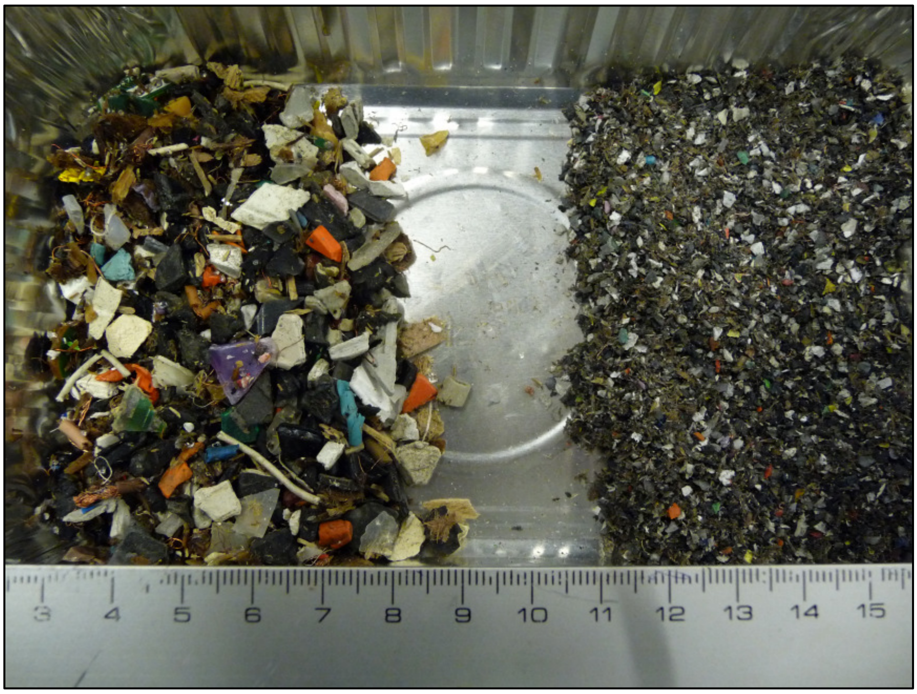

Figure 3.33 - Mixture of plastic / stone / glass / copper.

The density of these three materials has been measured through a gas pycnometer.

Material	Experimental Density	Colour
Copper	8861 kg/m^3	Red
Aluminium	2739 kg/m^3	Gray
Plastic / Stone / Glass / Copper	1459 kg/m^3	Mixed

The density of the mixed fraction (plastic/stone/glass/copper) has been evaluated as an average density. The mixed fraction is mainly composed of plastics; therefore the average density is lower than the density of stone, glass and copper.

3.3.1 The magnetic fluid

A magnetic fluid with a factor dilution of 1:5 has been prepared (i.e. 19,33 litre of water and 4,83 litre of magnetic fluid). The density of the fluid is 1031 kg/m^3.

The magnetization has not been measured with the same equipment of the previous test, but through a simple proportion. If the magnetization of the pure fluid is 18000 A/m, the magnetization of a fluid with a dilution factor of 1:5 is 3600 A/m.

Bucket	Magnetization	Density
1	3600 A/m	1031 kg/m^3

3.3.2 Sink-Float tests

According to the profile below it is possible to suppose the floating height of each material depending on its density.

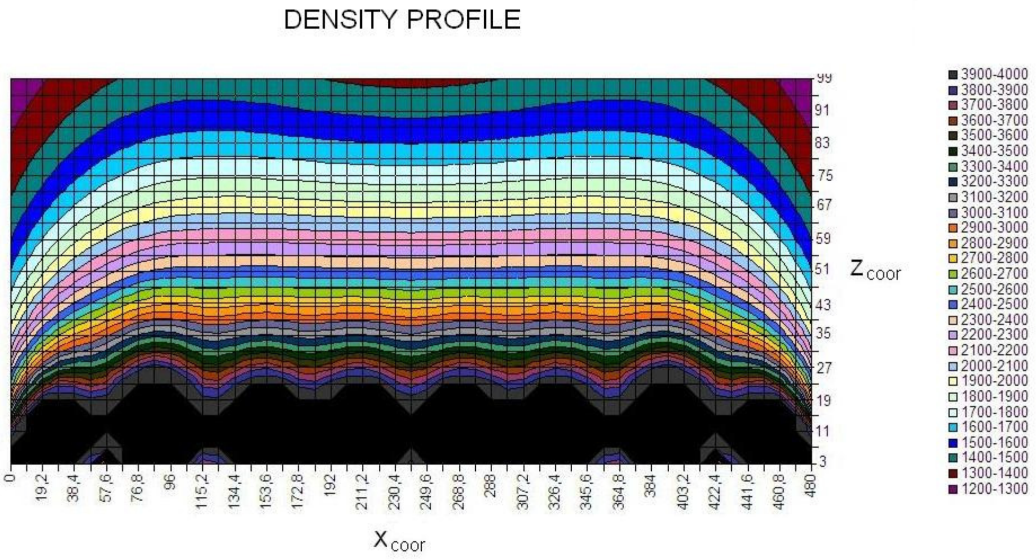

Figure 3.34 - Density profile in a ferrofluid with a dilution 1:5 and a magnetization of 3600 A/m.

Copper is supposed to sink. It can be recovered in the first sieve. Aluminium floats in the second and third section. The mixed fraction composed of plastic/stone/glass/copper is supposed to float into the fifth section.

Material	**Theoretical Floating Height (from surface of the magnet)**	**Section of outlet**
Copper	0 mm	1
Aluminium	43 ÷ 45 mm	2 - 3
Plastic / Stone / Glass / Copper	91 ÷ 97 mm	5

This last result is not true because of the average value chosen for the density: really the materials are subjected to separation during the process, therefore the theoretic floating height of each main component (PVC, stone and glass) should be evaluated in relation of the density, as shown in the table below (reported densities of PVC, stone and glass refer to an average value).

Material	**Theoretic Density**	**Colour**
PVC	1425 kg/m^3	Red
Stone	2700 kg/m^3	Gray
Glass	2755 kg/m^3	Mixed

Copper wires are expected to end up in the first section (bottom of the separator), stone and glass in the second and third section, PVC into the fifth section.

Material	**Theoretical Floating Height (from surface of the magnet)**	**Section of outlet**
PVC	91 ÷ 97 mm	5
Stone	43 ÷ 45 mm	2 - 3
Glass	43 ÷ 45 mm	2 - 3

Some sink-float tests have been carried out in order to evaluate the height of each material in a magnetic fluid column. On the basis of results, it is possible to know if the theoretic floating heights match with experimental floating heights.

Material	Experimental Floating Height (from surface of the magnet)	Section of outlet
Copper	0 mm	1
Aluminium	20 ÷ 30 mm	1 - 2
Plastic / Stone / Glass / Copper	60 ÷ 100 mm	3 - 4 - 5

Copper sinks at once during the test: then it is found in the first section. The aluminium floats just above the surface of the magnet and ends up in the second and third section. The mixed materials derived from WEEE spread into lighter fractions, from the third to the fifth sieve. If the separation is good, stone and glass should be found together with aluminium in the same section, while PVC should be found into the fifth sieve.

3.3.3 Time of separation

With reference to a magnetic fluid with a dilution factor of 1:5, the time for the particles to reach their floating height has been evaluated.

The particles are fed within a range between 20 mm and 30 mm (from the bottom of the gutter), although a medium height of 25 mm has been studied. As shown in Fig. 3.35, copper needs only 0,20 seconds to reach the bottom of the gutter; also aluminium needs only 0,20 seconds to reach its position of equilibrium. Differently, mixed materials need 1,35 seconds to reach their distinctive position; if the separation is good, stone and glass follow the same destination of aluminium, while PVC ends up in the highest compartment.

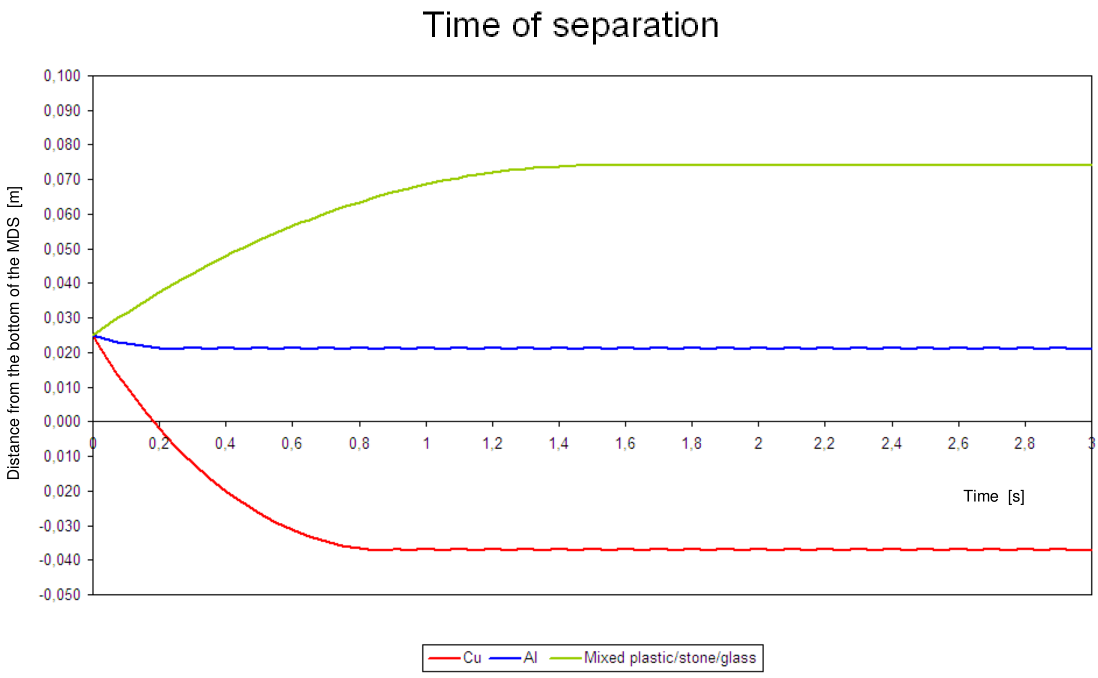

Figure 3.35 - Time for materials to reach the theoretical floating height.

3.4 The Experiments

The magnetic density separator has been modified in order to carry out the tests.

The vibration force is an important parameter for the tests. A vibrating device with power adjustment is necessary to avoid copper sinks suddenly (because of his density) in the bottom of the gutter without moving. Nevertheless strong vibrations inside separator cause leaks of fluid. For this reason the top of the gutter has been closed by means of an isolating tape (Fig. 3.36).

The accordance between shape of the materials and seize of the sieve is another important parameter. If the materials are in a spherical shape, like the plastics particles in the previous tests, there are no problems to collect the different fractions. If the materials are very small, like the mixture of plastic/stone/glass, or very thin, like the copper wires, they can not be easily handled. Often particles of plastic/stone/glass are inclined to group together and obstruct the course of the fluid through the sieve. Differently, the copper wires get stuck into the mesh of the sieve and it is very difficult to collect and analyze them. For this reason the usual sieve has been replaced by a textile (Fig. 3.37).

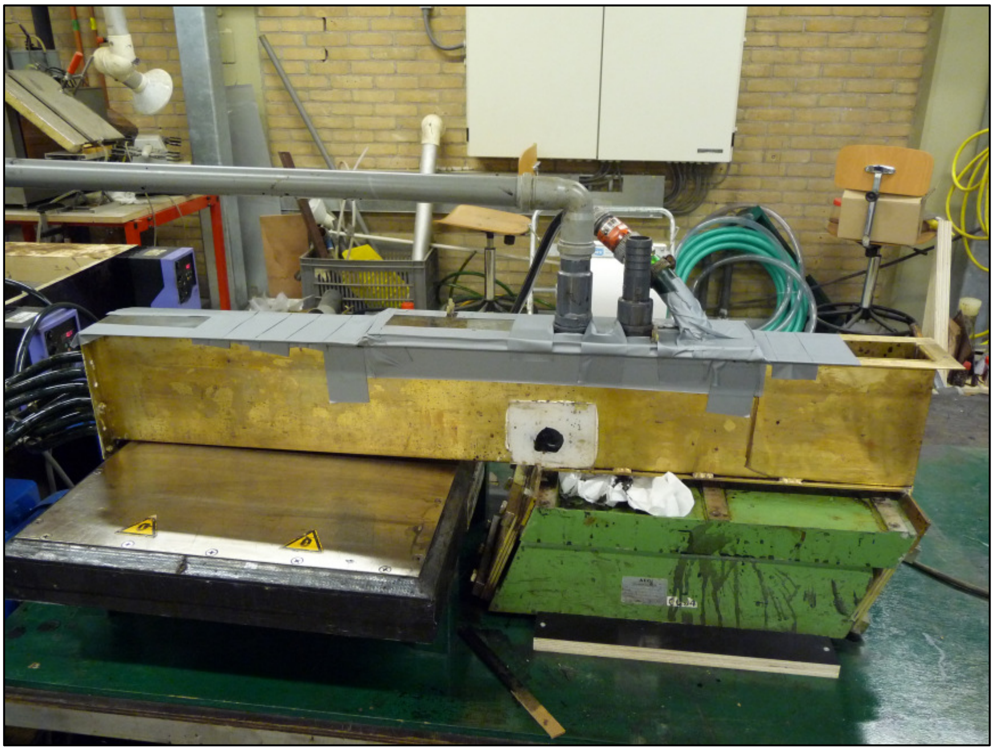

Figure 3.36 - Top of the gutter closed with isolating tape in order to prevent leaks of fluid.

Figure 3.37 - Textile over the sieve.

Unlikely this solution is not so practical: when the copper is collected, the fluid does not go beyond the textile.

Following test have been performed in order to find the best way to collect the most pure fraction of copper wires (which can be sold to the copper smelters).

3.4.1 Test n. 1

In the first test a sample of 20 grams of mixed plastic/stone/glass/copper has been analyzed. The aim of the test has been to obtain a pure fraction of copper, which can be sold to the copper smelters[2].

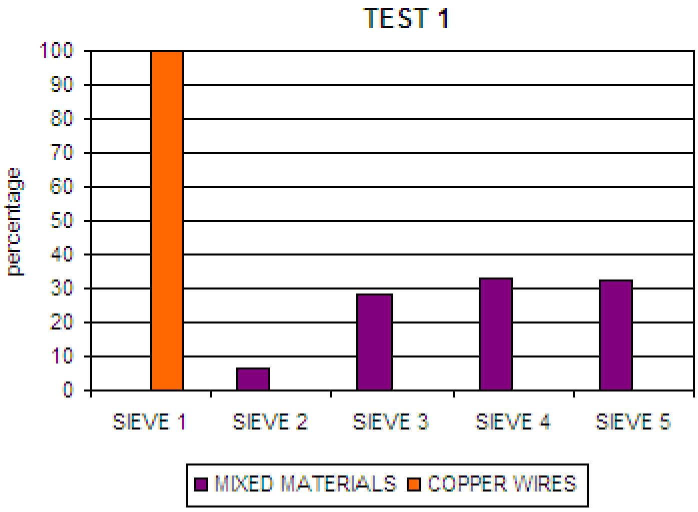

Figure 3.38 - Test results about WEEE separation.

Although some clogs of the sieve, a good level of separation is achieved. In the first sieve only pure copper is found (Fig. 3.38). Only a small quantity of mixed materials, without copper, is visible in sieve 2 (almost empty). From sieve 3 to sieve 5 all mixed materials are collected in a homogeneous way. The results are in accord with the data of the sink-float test. It is not possible to recover glass and stone: the materials are milled in such a tiny fraction that it is impossible to distinguish them.

With these materials and this kind of sieve it is possible to use only samples with weight < 20 grams to avoid any clog into the sieves.

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[2] Copper smelters in Europe require a maximum of 5% combustible material in the copper fractions that they process. Non-combustible materials such as stone and glass can be present at much higher percentages.

3.4.2 Test n. 2

A special sample has been prepared in laboratory: 10 grams of mixed materials derived from WEEE and 1 gram of copper in the shape of sphere (diameter of 1 mm) are fed together into the system. Aim of this second test has been to evaluate if different shapes of copper can affect the separation of the material.

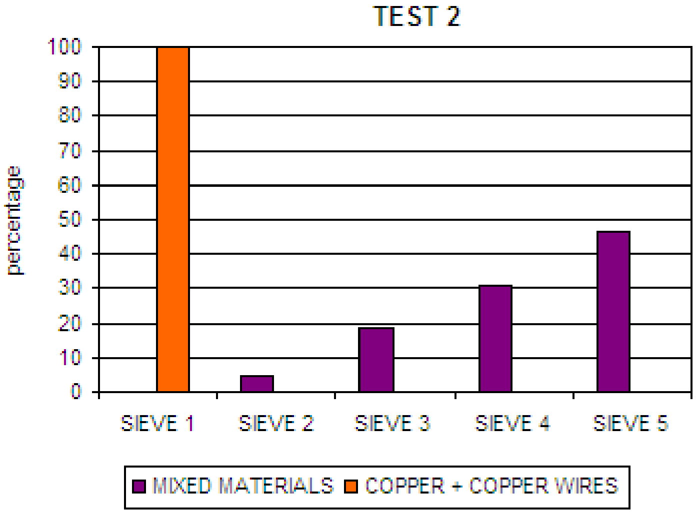

Figure 3.39 - Test results about separation between WEEE and copper.

As shown in Fig. 3.39, all copper is found in the first sieve, independently from its shape. By using copper in a spherical shape, therefore bigger and heavier than the wires, a stronger vibration force is required to avoid copper particles halt in the bottom of the gutter. The maximum vibration (3000 vibrations/minute) for at least 2 minutes is required in order to collect all copper into the first sieve.

3.4.3 Test n. 3

This test has been carried out in order to investigate either the separation process between copper and aluminium or the required vibration force to collect all metals into the sieve. The results of this separation are not quantitative, but only qualitative.

When the test has started the vibrating device was working at 50% of its power (i.e. 1500 vibrations/minute). After 2 minutes only aluminium is collected and no copper is found into the sieve. Aluminium is collected into the first and the second sieve, as expected from the sink-float test. The vibration force is gradually increased, with steps at 70%, 80% and 100% of the power of the vibrating device. The copper is found into the sieve only when the vibration force is set to the maximum value. By the strongest vibration the copper reaches the first sieve.

The separation between these two metals can be achieved according to the vibration force necessary to get out the material. At the first time the vibration is weak (70% of the power) and only aluminium arrives into the first sieve. The aluminium is collected and the sieve is empty again. Then the vibration is increased and all copper arrives into the first sieve.

3.4.4 Test n. 4

Thanks to the previous test aluminium is carried to the first and second sieve. A further test has been performed in order to separate copper and aluminium. The connections between sections of outlet and pumps have been changed, as shown in the following table.

Pump number	Related sections
1	1 and 10
2	2 and 3
3	4 and 9
4	5 and 6
5	7 and 8

The separation has been entirely successful: as expected, all copper is found into sieve 1 and all aluminium into sieve 2 (Fig. 3.40).

At the beginning of the test the vibration force is set to 70% of the power, so that only the aluminium ends up into the sieve. After 2 minutes the vibration force is increased till the maximum value and the copper moves towards the sieve.

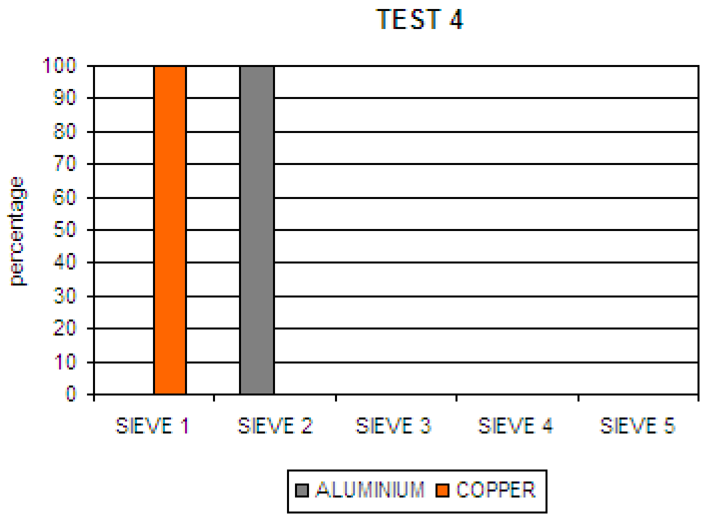

Figure 3.40 - Test results about separation between copper and aluminium.

3.4.5 Test n. 5

Copper in a spherical shape, aluminium and mixed plastic/stone/glass/copper have been taken under exam for the final test. The connections between pumps and gutter are the same of the previous test.

The description of the results about copper as well as aluminium is possible by means of the x-ray analysis. XRF is an analytical method to evaluate the chemical composition of all kind of materials.

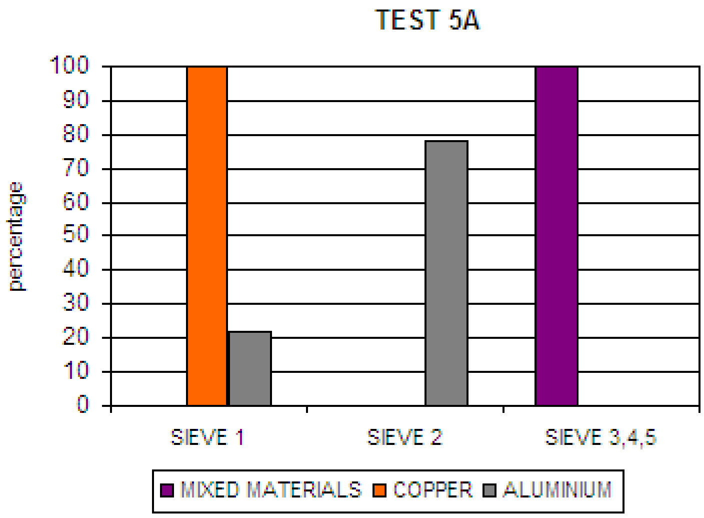

Figure 3.41 - First test results about separation among copper, aluminium and WEEE by means of the maximum vibration force.

With the maximum vibration force (3000 vibrations/min) the separation is not accurate (Fig. 3.41): the strong vibrations cause turbulence inside area of separation.

Even if the copper is collected into the first sieve, the aluminium is found not only in second sieve (as expected) but also in the first one (unexpected). All the light materials are found in the higher sections.

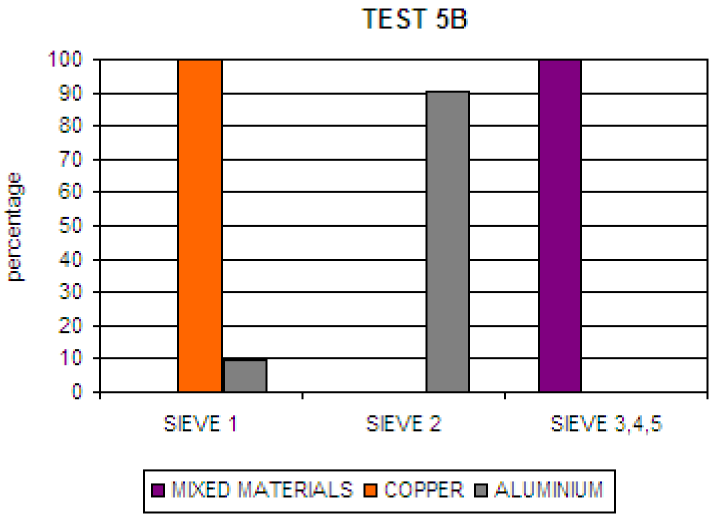

Figure 3.42 - Test results about separation among copper, aluminium and WEEE by means of a gradually increased vibration force.

In the second test (Fig. 3.42) the vibration force is increased gradually from 70% to 100% of the power.

The separation is more precise: it reaches the maximum value only when aluminium and light materials are already in the sieve.

Copper is found in sieve 1. Only a small part of aluminium is collected to the first sieve, while the main part is found in the second sieve.

Plastics and the other lighter fractions are found in the higher sections.

Chapter 4

Conclusions and future developments

4.1 Conclusions

The magnetic density separation allows separation into multiple fractions at once. The first test for the separation of diamonds from other gangue minerals has given promising results, even though some problems were still open.

Thus the system has been optimized through a new configuration. The layout of the gutter has been changed and new pumps, which can be regulated separately, have been used.

After the rebuilding of the separator, some tests have been carried out either with plastics or with materials derived from WEEE.

The first test has been carried out with PET, PMMA and ABS. The materials consist of cylindrical particles with a diameter of 2 mm. Different parameters, which can affect the separation, have been taken under consideration.

First of all, the separation of a wetted sample in comparison with the separation of a dry one has been studied. If the sample is wetted with a steam jet before entering into the system, the separation is more accurate. In fact the steam wetting avoids air bubbles cling to the surface of the sample.

The second parameter has been the frequency of the pumps. The pumps were over-measured for this gutter, thus they were forced to work at 20% of their nominal capacity. If the frequency is increased, air bubble and foam are visible on the surface of the fluid, and the highest pump works intermittently, because the fluid level into the gutter is not high enough. Thus 10 Hz is the right frequency of work: air bubbles are not visible and all pumps work continuously.

As third step, the interaction among particles of the same kind of material during the separation has been investigated. If the sample is fed all in once into the system, the clog of the connection between tubing and pump can occur. For this reason it is very important to feed the materials using a vibrating feeder: the samples enter gradually into the system and the connections hare not obstructed. The separation is also more precise.

Interaction among different kind of materials has been investigated as well. The materials agglomerate in the horizontal direction. Thus the movement of the materials along vertical direction is avoided and particles can not reach their position of equilibrium. With reference to the interaction between two different materials, if the sample consists of much more heavy than light fraction, the heavy fraction takes down the light one. The sample should be as homogeneous as possible to avoid a dangerous interaction between different materials.

The height of the gutter is an important parameter. The sample is divided into multiple fractions according to the density of each material. Changing the height of the gutter, it is thus possible to define in which section the different fraction should end up. For these samples the gutter has been kept at 10 mm above the magnet (sections of outlet at 4 mm). In this way the lightest and the heaviest fraction are separated with precision, even thought the separation of PMMA is not so accurate.

A final test has been carried out under the best operative conditions:

- Homogeneous sample;
- Steam-wetted sample;
- Frequency of the pumps set to 10 Hz;
- Materials handling through a vibrating feeder;
- Sections of outlet placed 4 mm above the magnet.

The heaviest and lightest fractions are separated with precision. All PET is found in the first section, while all ABS is found in the last section, far from the surface of the magnet.

There are some problems for the separation of the intermediate fraction. It is not possible to carry all PMMA particles in only one sieve.

The causes of this problem can be found in many factors, as the distribution of the apparent density of the fluid, air bubbles clung to the particles and interaction among materials into the area of separation.

The apparent density of the fluid is supposed to be constant along x direction (flow’s direction). Nevertheless it decreases at the beginning and at the end of the magnet. Moreover low density trenches are visible till to 30 mm of distance from the surface of the magnet. This irregular distribution can affect the separation of the materials. The sample can end up in lower fraction because of the decrease of the apparent density at the end of the magnet or low density trenches close to the surface of the magnet.

Air bubbles can influence the separation because they cling to the surface of the material, decreasing its own density. In that way the material unexpectedly ends up in lower fractions. Therefore the wetting method should be improved.

The interaction between particles can affect negatively the trajectory of the materials, which are supposed to be separated in the intermediate levels. While heaviest and lightest materials reach their position of equilibrium, the intermediate materials remain in the middle of the flow and are subjected to the variation of the flow. Moreover when other materials go to upper or lower fraction, intermediate materials can be trapped and taken up or down.

Other tests have been carried out with materials given from Axion Polymers Ltd. These materials come from WEEE: they consist in a mixture of plastic, stone, glass and copper wires. The tests have been focused on the recover of a pure fraction of copper (that can be sold to the smelters).

The copper is a heavy material and sticks on the bottom of the gutter without moving towards. For this reason a strong vibration force must be applied to the gutter. The top of the gutter has been modified in order to avoid losses of fluid, caused by the mentioned strong vibration force.

The first tests have shown that it is possible to separate a really good fraction of copper. Copper is found only in the first section, while other materials (like plastic, stone and glass) form the lighter fraction. It is not possible to obtain a further separation in lighter fractions (i.e. to recover glass and stone from plastic) because the samples are too tiny: when they are wetted by the fluid, they form a compact mass that causes the obstruction of the sieve.

Also the copper wires are very tiny: they get stuck into the mesh of the sieve. To solve this problem it is important to build a new wider gutter, where bigger materials can be processed.

Other tests have been carried out by adding aluminium. The possibility of getting three different fractions has been investigated.

Copper represents the heaviest fraction: the whole material is found into the first sieve. Other mixed materials derived from WEEE represent the lightest fraction. They can be recovered into the third, fourth and fifth sieve. Aluminium represents an intermediate fraction. It is mostly found into the second sieve, but a certain quantity is recovered into the first sieve too.

The separation of the intermediate materials is always problematic and should be in-depth investigated.

During these tests, the magnetic density separation has shown his enormous potential. Materials characterized by different densities can be separated into multiple density-fractions in only one step and in only few minutes.

Even though the results have been satisfactory, several problems still persist.

In order to improve the process of separation, the following aspects should be taken under serious consideration:

- A new magnet should be designed. The new magnet should ensure a constant distribution of the apparent density along the flow's direction, without low density trenches.
- A new gutter should be build to have the chance to test bigger materials.
- A more detailed analysis of the flow's conditions should be done. Particular attention should be paid to the flow of a magnetic fluid subjected to a non-homogeneous magnetic field. The aid of software of simulation is suggested.
- The interaction among particles of different materials inside area of separation should be prevented.
- Tests with different materials should be carried out.

4.2 Future developments

The construction of a new magnetic density separator is now in progress. The process will be similar to the previous one.

One big change will concern a new wooden gutter, which is 300 mm wide (five times bigger than the current one). It will be placed over a special support, which includes the magnet and a new bigger vibrating device.

The magnet will be replaced with a new one, which guarantees a density distribution inside the fluid as constant as possible. The density will be constant along X direction, from the beginning to the end of the magnet. Moreover low density trenches (visible till to 30 mm of distance from the surface of the magnet) will disappear.

The gutter will be divided in different areas. In the first area the fluid is collected, while the samples are directly entered into the area of separation by a special inlet. The laminator (made of straws) will be 100 mm long and ensures a laminar flow in the whole area of separation. The area of separation above the magnet will end with five different sections. Each section is 20 mm high and it is connected with a pump, which carries the material to the sieve.

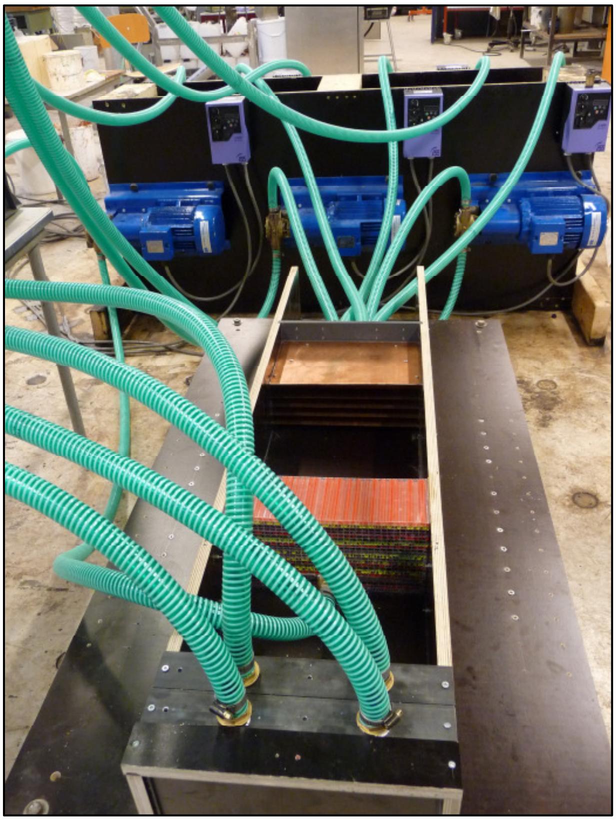

Figure 4.1 - The new magnetic density separator.

The different density fractions are pumped to the high part of the sieve. The grid is semicircular in order to dry the materials as much as possible. It is thus possible to recover high percentage of the magnetic fluid. The materials fall along the sieve and are collected in the bottom, while the fluid goes through the mesh and is collected in a basin under the sieve.

Therefore the main part of the recovered magnetic fluid comes back to the separator by gravity. The flow is regulated by four valves (one for each pipe).

A small quantity of liquid is transferred to another basin where it is mixed with sample of material in order to create slurry. The slurry is then pumped to the inlet of the system.

Figure 4.2 - Special inlet for samples and laminator.

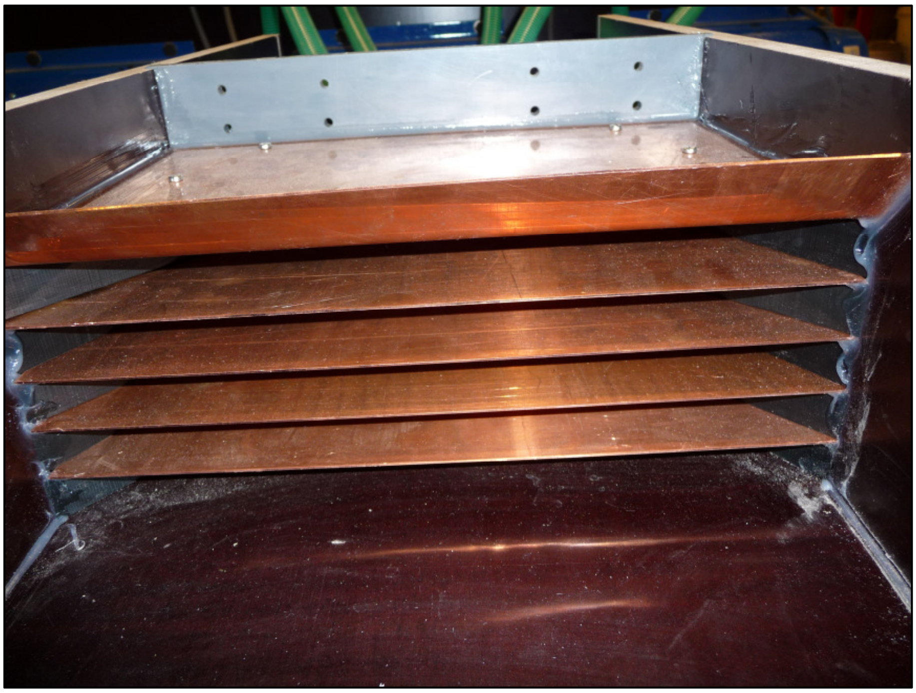

Figure 4.3 - Sections of outlet.

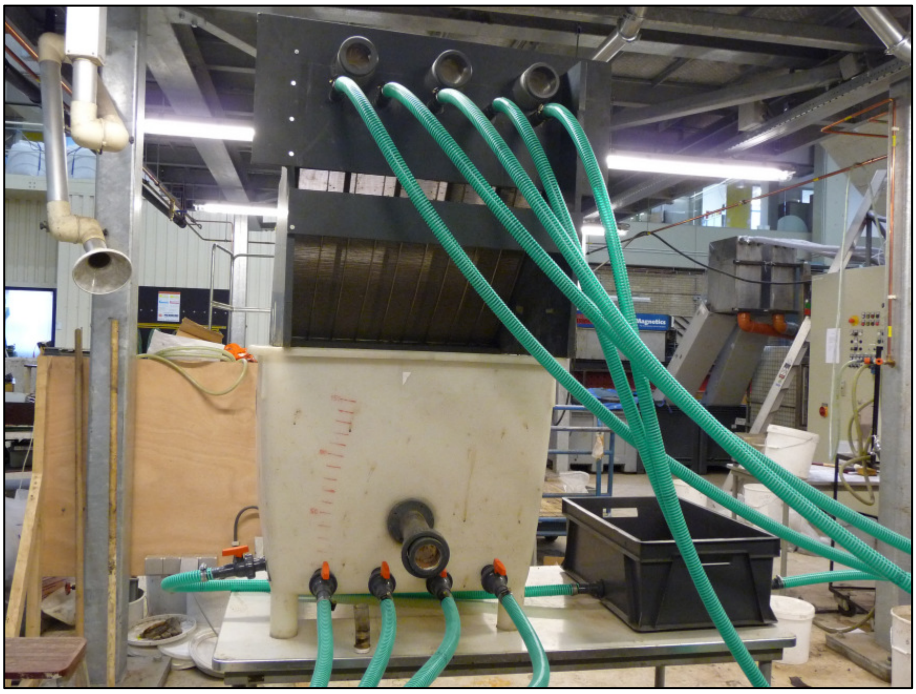

Figure 4.4 - View of the sieve. The higher tubing comes from the pump, the lower tubing goes to the separator.

Figure 4.5 - View of the sieve: particular shape that helps the drying of the materials.

4.3 Applications

The use of magnetic fluids is attractive for the separation of dense materials. Ferrofluids exposed to a non-homogeneous magnetic field acquire an apparent density exceeding densities obtained by conventional density-based methods.

The range of potential applications of magnetic density separation is extensive and this technique can change conventional practices of materials treatment. The main limitation is, however, the cost of ferrofluid, but the development of cost-effective, environmentally and user-friendly ferrofluids that can be easily recycled will enhance even further the significant potential of magnetic density separation.

Other problems are the limited throughput of the existing separator and the non optimal efficiency of separation of smaller materials. The magnetic density separation is, therefore, presently being used only on laboratory-scale.

The technology can be applied to the recovery of diamonds, gold and other platinum-group metals, recovery of non ferrous metals from scrap and to the treatment of wastes and tailings:

- The minerals industry faces problems of declining grades of ores, increasing proportions of deleterious impurities and a need to reduce the particle size in order to liberate the valuable components. New technologies capable of meeting these challenges have to be designed for environmental and sustainability reasons. Magnetic separation, unlike many other technologies of mineral treatment, can operate without the necessity of large quantity of water.
- The recovery of materials from solid waste is either technically or economically complicated. Nevertheless, beneficial uses for stockpiled by-products are being found, and recycling is experiencing increasing emphasis. While the process design from the environmental point of view is based on short-term thinking, sustainability requires a longer view, perhaps 50 years into the future. It is a tough problem, in which recycling and waste treatment, in addition to renewability, dematerialization and product life extension, is an important part of the scenario. The high intrinsic value of non-ferrous metals will inevitably lead to further improvements in the separation of fine and very fine particles of non-ferrous metals. This development, combined with the availability of more powerful magnets that would allow the increase in the magnetic field will extend the applicability of this technique and its viability.

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