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Chemical Engineering Journal 111 (2005) 85–90

Chemical Engineering Journal

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# Magnetic classification in health sciences and in chemical engineering

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**Abstract**

None of the present magnetic separators is capable of achieving the classification of particles according to their magnetic susceptibility. We have developed a new apparatus to attain these magnetic classification goals. In this paper, the design of the continuous-mode large-scale prototype of the magnetic classifier is presented. Many areas of application are foreseen for this device, and we analyse two of them – health sciences and chemical engineering – presenting also some possible application cases within these areas.


*Keywords:* Magnetic classification; Magnetic separation; Blood separation; Effluent treatment; Catalysis

## 1. Introduction

Magnetic fields are already commonly applied to achieve the separation or filtration of particles, cells, substances, etc. The most significant classical industries where magnetic fields are used to attain the separation and filtration goals are the minerals processing industries. In the last decade, with the enhancement of magnetic field strength (utilization of superconducting magnets or more powerful permanent magnets) and of magnetic separation capabilities by the indirect use of magnetic tagging and carrier techniques, the spectrum of areas where magnetic separation may be successfully applied has potentially (and in some cases effectively) increased.

However, the practical and industrial applications of magnetic separation are still very limited. One of the causes for this limitation is that none of the current industrial magnetic separators is capable of achieving a differential magnetic classification [1] of the particles present within the feed. In fact, the large majority of the present magnetic separators is only able to obtain three different outcome streams: the *Mags*—containing the particles with higher magnetic susceptibility, the *Tails*—containing the particles with lower magnetic susceptibility, and the *Middlings*—containing the particles with intermediate susceptibility.

In the last years, we have developed the first worldwide magnetic separator and classifier in order to attain these magnetic classification goals, mainly within the minerals processing area [1–4]. We are now trying to develop it fully regarding large-scale operations and also other areas of application. A paper was already published concerning some of the possible environmental applications and also presenting the design of the batch-mode large-scale prototype [5]. In the present paper, the design of the continuous-mode large-scale prototype, as applied to mineral and food processing industries, will be presented. After a brief introduction of the current status of the application of magnetic separation to other areas of science – health sciences and chemical engineering – some of the possible applications of the new device in these areas will be discussed. The major design modifications needed to perform in the device, in order for it to be operational regarding these application areas, will also be described.

## 2. The continuous-mode large-scale prototype

The design of the prototype for the batch-mode of operation has been already presented in [5], regarding its immediate applications in mineral and food processing industries. In Fig. 1, is presented the design of the prototype for the continuous-mode of operation, regarding the same immediate applications. The major modifications comparing to the

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doi:10.1016/j.cej.2005.02.013

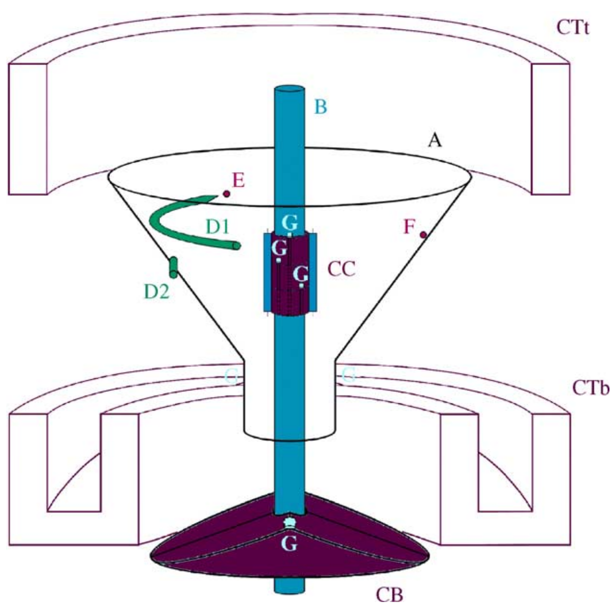


Fig. 1. Schematic representation of the continuous-mode large-scale prototype of the new magnetic separator and classifier: A: funnel-like trunk (which may rotate or not); B: superconducting straight wire cable; CC: central collector designed to collect magnetic particles by classes; D1 and D2: feeding systems for the rotating and static trunk configuration, respectively; E: particle fed at an initial radius $r_i$; F: magnetic particle; CB: central-bottom collector; CTt: outer collector (top section); CTb: outer collector (base section); G: air sprays.

batch-mode of operation model are mainly in the collecting systems. It is composed by a central superconducting magnet, which generates the magnetic field, by a funnel-like trunk on the surface of which the particles are introduced by two different feeding systems (depending on whether a rotating or a non-rotating trunk is used), and by three different collecting systems: the central one – which collects the differentially classified magnetic particles, the central-bottom one – which collects the particles possessing low magnetic susceptibility, and the outer one – which collects the particles presenting negligible magnetic susceptibility. All the collectors are specially designed to provide a collection of the outcomes in a continuously fashion.

The working principles of the new device are described in [2–4].

## 3. Potential applications

### 3.1. Health sciences

#### 3.1.1. Current status

Medical applications of magnetic separation have left the negligible level a few years ago. This was mainly caused by the development of magnetic carrier and tagging techniques [6], which are quietly revolutionizing this field concerning the application of magnetic separation.

Nowadays, the separation of biologically active compounds and cells may be achieved by two different ways [7]: when structures exhibit sufficient intrinsic magnetic properties (e.g. ferritin, haemoglobin, deoxygenated erythrocytes (in plasma), magnetotactic bacteria [8], etc.) separation may be achieved without any modification of the target material (Fig. 2); however when they do not (in most cases), they are tagged with or carried by magnetic particles, hence indirectly acquiring the magnetic properties needed and thus being successfully separated (Fig. 3). Nonetheless, in all these cases and in almost all the existing medical magnetic separating devices, only two components, at the most, are separated in one passage, and to achieve multi-separations, several passages through the same system or a cascade system of devices are required (Fig. 4).

#### 3.1.2. Major modifications required in the new device design

In order for the new device to be successfully applied to this scientific area, some major modifications in its design are foreseen, mainly regarding the trunk configuration, and the different collecting systems.

#### 3.1.3. Major potential advantages obtained by the application of the new device

Using the new device (with the design modifications pointed above) will enable us to separate many components

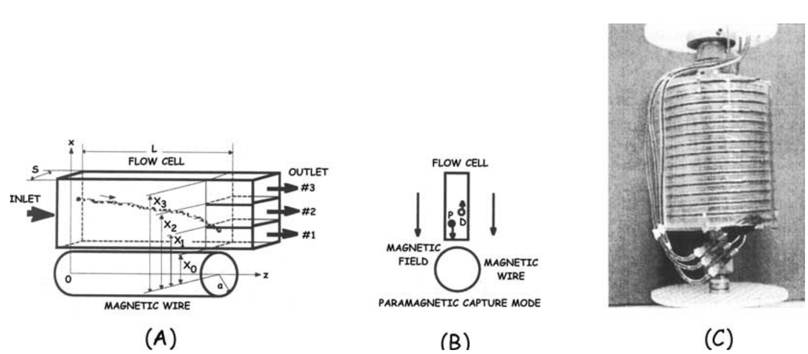


Fig. 2. Schematic diagrams – (A) and (B) and laboratorial prototype (C) of a continuous magnetic separator used to separate two blood components from whole blood (based on [9]).

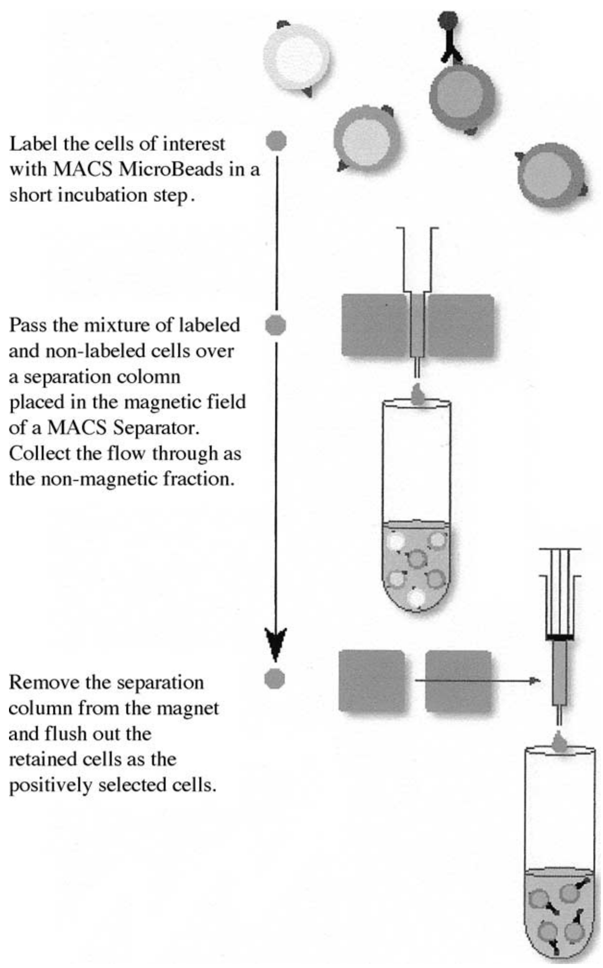


Fig. 3. Magnetic cell sorting using MACS technology (magnetically assisted chemical separation) (from [10]).

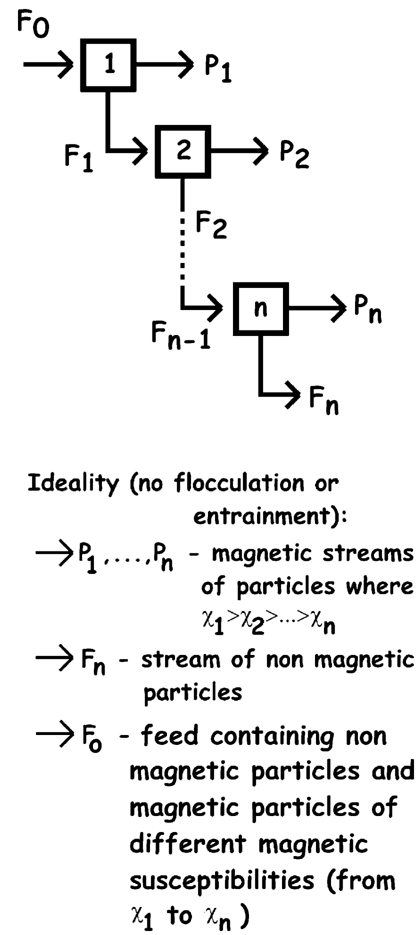


Fig. 4. Classical cascade magnetic separating process flowsheet (based on [1]).

on a single step, thus attaining the sorting process depicted in Fig. 4, but in a single step and on the same device without needing to perform a cascade procedure. It may be required to previously tag the different targets with particles possessing different predetermined magnetic susceptibility. Among the most important applications of the device in this area we mention the separation of blood components (useful, for example, in the treatment of leukaemia), the treatment of cancer in general terms and cell sorting.

### 3.2. Chemical engineering

Chemical engineering is a scientific area which contains a broad spectrum of fields. Thus, some of the cases presented in a previous paper [5] regarding some environmental applications may be considered also as potential applications within chemical engineering. In this section besides a deeper overview of some of the latter cases, other possible applications within chemical engineering will also be analysed.

#### 3.2.1. Current status of the application of magnetic separation in

*3.2.1.1. Water and gas filtration.* The filtration of particles present within aqueous or gaseous media, presenting

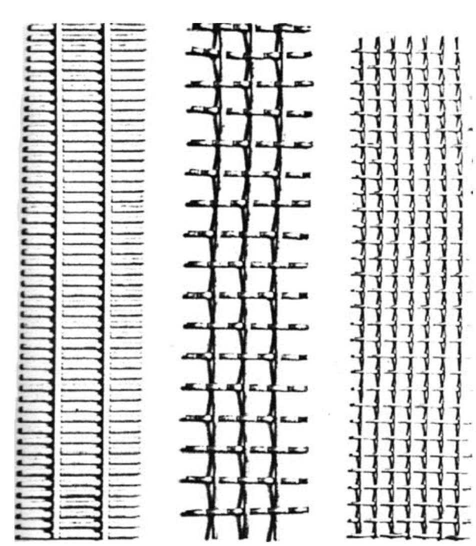

Fig. 5. Ferromagnetic matrices (from [11]).

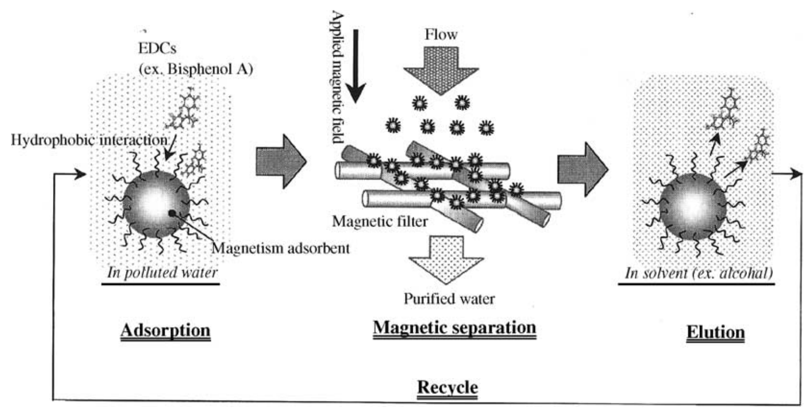


Fig. 6. Purification cycle of EDCs contaminated water (with the aid of magnetic carriers) (from [15]).

intrinsically high magnetic susceptibilities, is being achieved since the development of high gradient magnetic filtration (HGMF), decades ago. In fact, there are some typical industries that apply these kind of filters (which rely on the capture of the magnetic particles usually in ferromagnetic matrices, Fig. 5):

Water media: Steel industry – the waste water resultant either from the overall process, or either from the exhaustion gases cleaning processes (when wet scrubbers are used), contains several different pollutants (e.g. iron-bearing particles) which present non-negligible magnetic susceptibility values [11,12].

Power plants – the corrosion products present within the parts of thermal or nuclear power plants (e.g. iron-based, cobalt-based, nickel-based composites), quite often present non-negligible magnetic susceptibility values [11,12].

Gas media: Coal industry and power plants – fly ash from coal industries [11] and from power plants (the latter, after removal may be applied to ceramic and refractory applications [13]), contains several different pollutants (e.g. aluminium, iron or titanium oxides), which present non-negligible magnetic susceptibility values.

Steelmaking and siderurgical industries – the gaseous currents emitted by these industries contain several different pollutants (e.g. iron oxides) which present non-negligible magnetic susceptibility values [11,14].

*3.2.1.2. Water treatment.* The removal of contaminants present in water, by the application of magnetic fields has been expanding its way, accompanying the development of magnetic tagging and carrier technologies. In fact, the direct removal of some contaminants is only achieved in some special cases when the contaminant already presents a high value of magnetic susceptibility (e.g. removal of iron oxides, removal of calcium to prevent scale), hence other non-magnetic contaminants are only successfully removed after being tagged with magnetic beads or collected/adsorbed by magnetic carriers (see Fig. 6) – some classical examples of this are magnetic seeding [11,12,15–18] and magnetic flocculation techniques [19,20]. To perform the magnetic separation task, not only high gradient magnetic separators (HGMS) are used, but also open gradient magnetic separators (OGMS) like the drum separator presented in Fig. 7.

*3.2.1.3. Conjunction with hydrocyclones and cyclones.* The classification of particles or separation of fluids is often obtained by the utilization of hydrocyclones or cyclones. For many years magnetic systems have been coupled with this devices, in order to try to enhance their performance – by complementing the effect of the centrifugal force with a magnetic force created by a set of permanent magnets, electromagnets (Fig. 8) or superconducting magnets [21,22]. However, the efficiency of these magnetic hydrocyclones and cyclones has never reached industrial satisfactory levels.

*3.2.1.4. Recycling industries.* There are several industrial applications of magnetic separation in recycling. As a classical example we may point out the removal of scrap metals by drum magnetic separators (containing permanent or superconducting magnets). Presently, some other non-conventional applications are emerging, like the waste paper de-inking/recycling process with the aid of wet high inten-

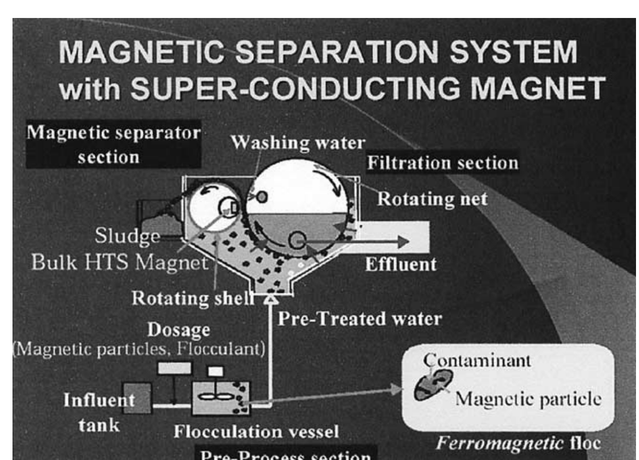


Fig. 7. Schematic diagram of water purification by magnetic flocculation (from [19]).

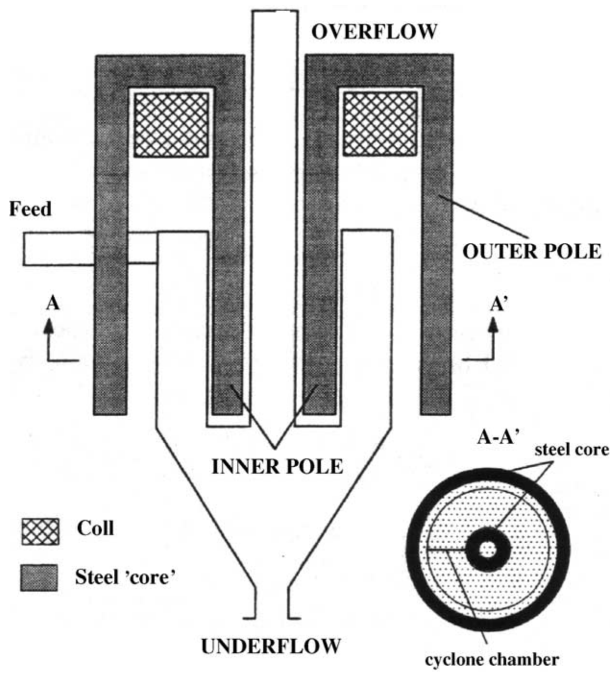


Fig. 8. Magnetic cyclone (after [21]).

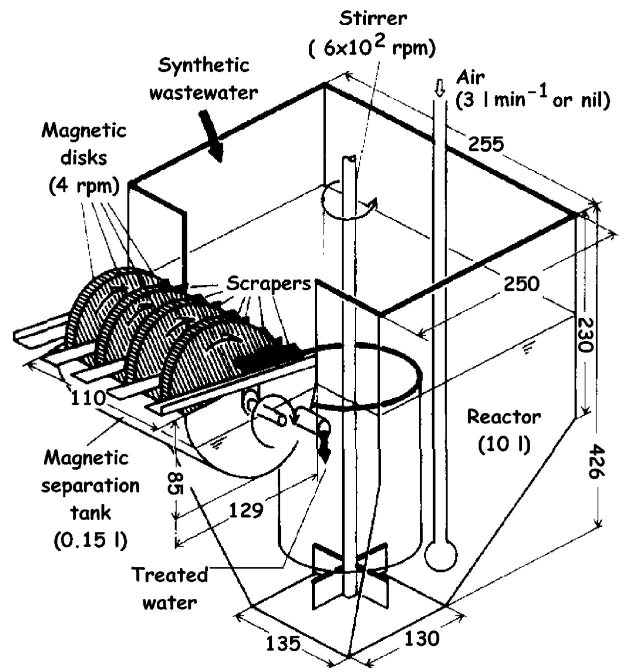


Fig. 10. Reactor with a magnetic separator tank to perform the recycling of bacterias (after [24]).

sity magnetic separation (Fig. 9) [23], or like the recycling of bacterias used in sewage treatment plants with the aid of magnetic particles and magnetic disc separators (Fig. 10) [24].

*3.2.1.5. Reaction chemistry.* Fluidized catalytic cracking (FCC) is a commonly used method in the petroleum industry to convert low-value long chain hydrocarbons existent in crude oil into high-value small molecules used in gasoline production [25]. In this process the used FCC catalyst becomes more and more contaminated with nickel, iron and other heavy metals each time it is used in and recycled to the process, hence, after a while, it must be separated, discarded and fresh catalyst is inserted. The separation step between the fresh, the low-contaminated and the more-contaminated FCC catalysts is usually done indiscriminately, thus some fresh and low-contaminated FCC catalysts are also withdrawn from the process (meaning a waste of resources). Because the contaminants of the used catalyst usually present high values of magnetic susceptibility, some methods were developed to apply drum magnetic separators, in order to achieve a better separation between the several 'species' of catalysts [25,26].

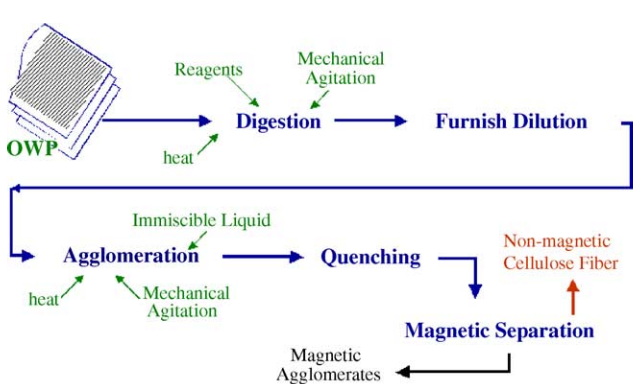


Fig. 9. Schematic diagram of the waste paper de-inking/recycling process (after [23]).

*3.2.1.6. All the previous cases, regarding multi-separations.* It is important to notice that, likewise in health sciences, in all the above pointed cases, only two components, at the most, are separated in one passage, using the majority of the current magnetic devices, and the achievement of multi-separations only occurs, if we use a cascade system of devices or if the feed is passed through the device several times.

### 3.2.2. Major modifications required in the new device design

In order for the new device to be successfully applied to this scientific area, and regarding the cases presented above, major modifications in its design are foreseen, namely concerning the trunk configuration, the feeding systems and the different collecting systems for the (case 3.2.1.4.), and concerning only the trunk configuration and the different collecting systems for the remaining cases.

### 3.2.3. Major potential advantages obtained by the application of the new device

The main advantage of the utilization of the new device (with the design modifications pointed above) in the cases presented, is the achievement of the separation of many components in a single step. Likewise in health sciences, in some particular cases it may be required to use magnetic tagging or carrier technologies. For the cases analysed in this section the main advantages expected are: the removal of contaminants from water, gases or other effluents (cases 3.2.1.1. and 3.2.1.2.); an increase in the efficiency of ordinary hydrocyclones and cyclones (case 3.2.1.3.); an increase in recycling efficiencies (case 3.2.1.4.) and an increase in the separation efficiency of spent FCC catalysts (case 3.2.1.5.).

## 4. Conclusions

Magnetic Classification, the new area of science created by the new apparatus we have developed, presents many potential applications in a huge spectrum of scientific areas. The continuous-mode large-scale prototype designed to be applied directly to food and mineral processing industries, shown in this paper, differs from the batch-mode model mainly regarding its collecting systems. Concerning the applications of the new device, two major areas were analysed: health sciences and chemical engineering. In what concerns the latter area, cases like water and gas filtration, water treatment, utilization of magnetic hydrocyclones and cyclones, recycling and reaction chemistry, were studied, while in the former area the study was focused regarding the cases of separation and classification of biological compounds or molecules, either presenting intrinsically strong magnetic properties, either requiring the use of magnetic tags or carriers to achieve high enough values for the magnetic susceptibility. In both chemical engineering and health sciences areas the process of analysis was the same (description of the current status of the application of magnetic separators in the case under study, major design modifications required to perform in the new device in order to be successfully applied, and major advantages foreseen resultant of the application of the new apparatus), to conclude that in all cases the possible application of the new apparatus (with the design modifications required) will improve the outcomes.

## Acknowledgements

Prof. Domingos Barbosa is acknowledged for all his help regarding this project. Fundação para a Ciência e a Tecnologia is acknowledged for its post-doc sponsorship with reference SFRH/BPD/6964/2001 (P.A. Augusto) and for its sponsorship regarding the participation in the conference solid–liquid separating systems IV. Prof. Fernando Concha is acknowledged for his sponsorship regarding the participation in the conference solid–liquid separating systems IV.

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