

# Development of an electromagnetic hydrocyclone separator for purification of wastewater

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## Abstract

A number of various organic and inorganic contaminants are commonly present in the technological fluids hindering production quality. Importantly, waste influents must be purified to meet the appropriate environmental standards for their disposal. This paper deals with the development of a treatment technique for technological and wastewater streams allowing the separation of microscopic droplets of water, sand, oil and other organic and inorganic contaminants. Some existing approaches and processes for treatment of contaminated fluids are briefly reviewed and the design of an electromagnetic hydrocyclone separator is presented in this paper. The effect of the main forces on the separation of small-sized impurities ( $<10\mu\text{m}$ ) is analysed. The experimental tests demonstrated the efficiency of the developed apparatus in purifying the industrial wastewaters of the textile dyeing industry.

## Introduction

Technological and waste fluids usually contain different types of micro-impurities such as clay, ferrous, phenol, oil, organic, paint and nuclear particles that affect the production quality. Therefore, there is a great demand for improved universal treatment and purification systems (i.e. filters, separators, etc.) for these fluids, which can boost production efficiency. Moreover, waste fluids should be filtered before their disposal to meet the environmental standards.

Different filters and separators have been designed to recover the contaminated particles from technological and waste streams. These apparatuses are mainly hydrocyclones, magnetic or electrostatic traps and membrane filters. In most cases, such apparatuses meet the demands of the industry, provided that the small-size impurities ( $<10\mu\text{m}$ ) do not interfere with the main technological processes. A number of articles authored by Mustafayev & Gutman (1969), Banks (1987), Sozov (1987), Oder & Taylor (1990) and Durst & Trautman (2005) discuss the efficiency of these filters and traps for different types of impurities and different concentrations of these contaminants in fluids and gases.

The magnetic field has been successfully applied for separation purposes and this technology has been covered in the scientific literature. A review of the

main principles, different devices and several applications has been provided by Obertteuffer (1974) and Khalafalla (1976). This approach is widely used not only for the extraction of magnetic metals but also for wastewater treatment in metallurgy (Habarov 1976), for magnetization of boiler water in power stations (Klassen 1982) and various other applications (Ali-Zade *et al.* 1997). The discovery of unexpected magnetic interactions between ultra small specks of rust has led scientists to develop a revolutionary, low-cost technology for cleaning arsenic from drinking water (Boyd 2006).

The electric field was also successfully applied in powder technology, in 'dusty' industries to protect the air quality and the surrounding environment (Lali *et al.* 1989; Ulaby 2001) and for the purposes of radioactive particles' separation. Some methods and designs of filter separators are based on the joint action of electric and magnetic fields. Other designs are based on the joint action of three forces: electric, magnetic and centrifugal as it can be found in an electromagnetic cyclone (Ali-Zade *et al.* 1991, 1992, 1994, 1997; Durst & Trautman 2005). This method and apparatuses based on these principles are also used in the uranium and nuclear fuel processing technologies (Ozawa 1984).

The efficiency of these filtration methods is evaluated by the impurities factor (IF), which is the impurities-to-

pure matter ratio before and after filtration. There are many 'delicate' technologies that require extremely low IF because even a very small volume (0.1% and less) of the microcontaminants can result in a severe malfunction or accident. Among others, such cases include the following:

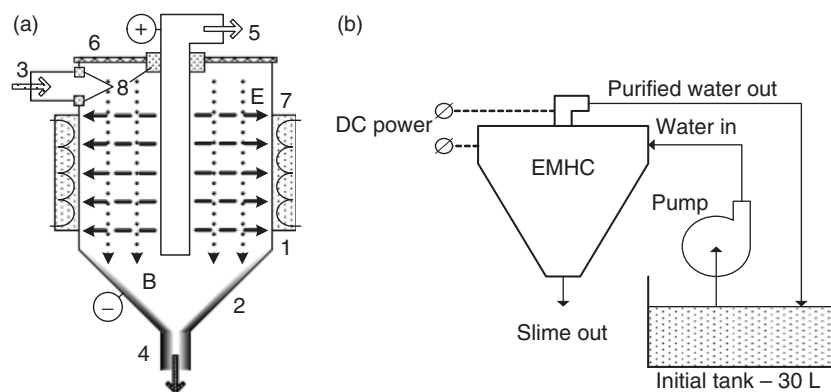
1. A very small amount of microscopic water droplets in a airplane fuel ( $<0.01\%$ ) can cause accidental failure of the engine, because water may freeze in the valves or in narrow pipes, and fuel cannot be pumped into the engine. The filtration process of these micrometer-sized water droplets is usually achieved with the help of special chemicals, but this method is somehow complicated and expensive.
2. The small amounts of phenols and other light organic impurities existing in the distilled water of thermal plant boilers cause cavitation, leading to damage and erosion of the pipes. This increases the risk of steam leakage or even explosion of the boiler. Separating these particles by means of existing mechanical or chemical methods is extremely difficult and expensive.
3. Demineralization or desalination of different liquids (particularly sea water) is achieved by mixing the liquid with another active supplementary liquid (or a fine powder), which entraps the appropriate mineral salts, and then separating the liquid or the powder from the main product. The smaller the microparticles of the entrapping agent, the more effective the entrapping process can be. One of these active and rather cheap liquids is kerosene. Separating the salty kerosene microdroplets from the mix using an ordinary hydrocyclone is very difficult, expensive and inefficient. Here, application of additional electric and magnetic forces would provide higher efficiency than use of the centrifugal force alone.
4. Trapping and filtering out different nuclear particles from fluids have become very important issue. Currently, this process is being successfully implemented in Ukraine to reveal and to filter out electrically charged nuclear particles from milk by using electric and magnetic forces.

When quality separation of liquids from different impurities (including microparticles) is of importance, the application of additional separation forces results in a more effective purification process. Therefore, it was proposed that the electromagnetic forces would result in an improvement of filtration efficiency. Here, the main effect arises from the exceptional performance of the suggested technology, higher reliability and a wider margin of environmental safety. This paper deals with development of an electromagnetic hydrocyclone (EMHC) separator and its application for wastewater treatment.

## Background of the technology

EMHC is a complex apparatus developed for the treatment of technological and waste liquids (Ali-Zade *et al.* 1997). A special design of the EMHC combines electric, magnetic and centrifugal forces in order to separate the impurities from liquid. Similar to traditional hydrocyclones, there are several designs of EMHC, such as cylindrical and conical EMHC, used for separation of two products (Fig. 1a). EMHC consists of a cylindrical main body 1 made of diamagnetic metal (or plastic); a conic ferromagnetic metal core body 2; an input pipe 3 tangential to the main body; an outlet pipe 4 for heavy influent, and a central outlet pipe combined with a central electrode 5 for light-weight product, a flat and round cover 6 made of ferromagnetic metal, a bobbin 7 around the main body and electrical isolation of the pipes 8. The design of the EMHC was patented and discussed by Ali-Zade *et al.* (1991, 1992, 1994, 1997).

As illustrated in Fig. 1(a), the electric field force is produced by the direct current (DC) voltage applied between the main body and the central outlet pipe. A bobbin around the main body produces a magnetic field between the flat ferromagnetic cover and the magnetic conical (or flat) bottom of the EMHC. There is an inertial centrifugal force due to the high-speed flow of the fluid within the main cylinder, because of the tangential set-up



**Fig. 1.** Design of the electromagnetic hydrocyclone (a) and experimental setup (b). EMHC, electromagnetic hydrocyclone; DC, direct current.

of the input pipe. The velocity of the incoming flow is equal to the fluid tangential rotation velocity.

In some cases, ozone ( $O_3$ ) can be generated around the central electrode to provide a fungicidal action, useful in oxidizing undesired inorganic or organic contaminants. To realize this feature, an additional high-frequency voltage is applied to this electrode through a capacitor (this option was proposed by Ali-Zade et al. 1997).

The technological or waste fluid enters the apparatus through the input pipe and heavy particles, such as sand, silt, clay, metals, etc, are driven by the centrifugal force towards the inner cylinder of the main body, and are expelled via the conic exit. Light-weight particles, such as oil and organic substances, gas and so forth, are redirected towards the central electrode pipe and driven out of the EMHC. This system is capable of providing a very high-quality filtration (especially for micrometre-size impurities) due to the additional action of the electric and magnetic field forces applied colinearly with the centrifugal force. The design of the apparatus allows these three main forces to act in the same direction.

The following vector forces affect the flow of a particle in EMHC (Mustafayev & Gutman 1969; Khalafalla 1976; Sozov 1987):

$$F_m + F_e + F_s + F_i + F_a + F_w + F_c = 0, \quad (1)$$

where  $F_m$  is the magnetic force;  $F_e$  the electric force;  $F_s$  is Stokes' force (resistive);  $F_i$  the inertia force;  $F_a$  the Archimedes force;  $F_w$  the weight force;  $F_c$  the centrifugal force.

A comparative analysis by Sozov (1987) demonstrated that the influence of  $F_a$ ,  $F_i$  and  $F_w$  on a very small particle ( $< 50 \mu m$ ) is imperceptibly insignificant and therefore can be omitted, as the behaviour of very small particles is governed by the forces  $F_m$ ,  $F_e$ ,  $F_c$  and resistive force  $F_s$  (which depends on the viscosity of the fluid).

The effect of the centrifugal force on particle filtration is determined according to Obertteuffer (1974):

$$F_c = \frac{\pi d^3 (\rho_1 - \rho_2) v_t^2}{6r}, \quad (2)$$

where  $d$  is the diameter of the particle (m);  $\rho_1$  the density of fluid ( $kg/m^3$ );  $\rho_2$  the density of the particles ( $kg/m^3$ );  $r$  an average revolving radius (m); and  $v_t$  the velocity of the particles (m/s). When  $\rho_1 < \rho_2$  (water with heavy impurities, such as ferrous particles, sand, etc.), purified liquid is expelled through the central pipe and heavy particles are removed at the bottom using a conical pipe. When  $\rho_1 > \rho_2$  (water with oil, phenols, etc.), purified liquid is extracted through the bottom conical pipe and a fraction of oil is removed from the central pipe. Importantly, most of the micrometre-sized particles cannot be settled or precipitated to the tank bed by the gravity force: for  $d < d_{critical}$  smaller weight of microparticles (proportional

to  $d^3$  of a particle) cannot overcome the higher floating force on a particle (which is proportional to  $d^2$ ).

Generally, up to 70–80% of the particles in technological fluids carry a negative electric charge as specified by Klassen (1982), Sozov (1987) and Oder & Taylor (1990). Electric and magnetic forces have a higher influence on the negatively charged microparticles than the centrifugal force. Therefore, charged microparticles can be effectively repelled or attracted to the electrodes. Here, the central pipe is used as a positive electrode and the cylindrical body as a negative one. There are some additional inlets in the central pipe that can be set higher for collecting light-weight and charged particles, such as oil, gas bubbles, acetone, phenols and so on. The electric force affecting the charged particle is characterized as (Ulaby 2001):

$$F_e = Eq, \quad (3)$$

where  $E$  is the electric field strength (V/m);  $q$  the average electric charge of a particle (C). The radial electric field intensity value of EMHC,  $E$ , can be determined in a manner similar to the value of the electric field of the cylindrical capacitor (Ulaby 2001):

$$E = \frac{V}{r \ln R/r_{CE}}, \quad (4)$$

where  $V$  is the applied voltage (V);  $R$  an internal radius of EMHC (m);  $r_{CE}$  the radius of the central pipe electrode (m); and  $r$  the variable value of EMHC radius (m).

The intensity of the electric field depends on the distance from the electrode; it reaches its maximum around the central electrode when  $r=r_{CE}$ , and it has its minimum around the outer cylindrical electrode when  $r=R$ . The average electric charge of a particle  $q$  [in Coulomb (C)] was calculated according to Ulaby (2001):

$$q = \frac{\epsilon_0 \epsilon S \xi}{\delta}, \quad (5)$$

where  $\epsilon$  is the relative permittivity, for the majority of the discussed cases,  $\epsilon/\epsilon_0 \approx 81$  (Ulaby 2001);  $\epsilon_0$  the dielectric constant of air (in vacuum),  $\epsilon_0 = 8.86 \times 10^{-12}$  (F/m);  $S$  the surface area of the particle (for an 'average' particle of  $d=10 \mu m$ ,  $S=\pi d^2=3.14 \times 10^{-10} m^2$ );  $\xi$  the electro-kinetic potential of the particle (V) (usually,  $\xi=0.1-0.5$  V and may become higher for some organic products, according to Ulaby 2001); and  $\delta$  the thickness of the double electric layer (m) ( $\delta=10^{-6}$  m as per as Ulaby 2001).

Thus, using Eq. (5), the charge of a particle with diameter  $d$  can be estimated as:

$q = 2 \times 10^{-14} - 6 \times 10^{-14} \text{ C}$  for a particle of size  $10 \mu\text{m}$ ,  
 $q = 0.5 \times 10^{-14} - 1.5 \times 10^{-14} \text{ C}$  for a particle of size  $5 \mu\text{m}$ ,  
 $q = 0.125 \times 10^{-14} - 0.375 \times 10^{-14} \text{ C}$  for a particle of size  $1 \mu\text{m}$ .

There are two main magnetic forces that must be considered in this case as discussed by Habarov (1976), Khalafalla (1976) and Oder & Taylor (1990). The first governs the behaviour of the magnetic particles only (Ulaby 2001):

$$F_{qm} = Hq_m, \quad (6)$$

where  $H$  is the intensity of the magnetic field strength (A/m);  $q_m$  the magnetically induced charge on a particle (C). As far as the separation of light-weight organic droplets (i.e. oil, phenol, etc.) from water is concerned,  $q_m$  is very small as discussed by Habarov (1976) and later by Oder & Taylor (1990), the magnetic field is homogeneous and, therefore, the magnetic force can be neglected.

The second magnetic force described by the Hall effect is taken into account in this case. Here, any movement of an electrically charged particle [as governed by Eq. (5)] in the magnetic field creates the force that helps to reinforce the particles' separation process (Ulaby 2001):

$$F_H = qBxv, \quad (7)$$

where  $q$  is the charge of a particle (C);  $B$  the induction of the magnetic field;  $v$  the particle velocity (m/s); and  $x$  the vector multiplication symbol.

In the designed EMHC, the centrifugal, electric and magnetic forces act along the same radial direction and help facilitate the separation process, which is especially effective in the case of microparticles.

## Design considerations

The EMHC was designed using the following parameters: diameter of the particles  $d=1, 5$  and  $10 \mu\text{m}$ , average revolving radius  $r=0.1 \text{ m}$ , velocity of inlet water (and charged particles)  $v=0.5\text{--}1.0 \text{ m/s}$ , particle charge  $q=(6\text{--}0.375) \times 10^{-14} \text{ C}$ , applied voltage  $V=600 \text{ V}$ , and volume capacity  $V_v=5 \text{ L}$ ,  $r_{CE}=25 \text{ mm}$ ,  $r_{in}=25 \text{ mm}$ . The resulting EMHC is a rather powerful apparatus with an expected power consumption of  $0.175 \text{ kWh/m}^3$  of wastewater. Water polluted by small volumes of phenol (emulsion) was considered in this preliminary design.

The calculations for several variants of particle diameter  $d$  and its charging ability  $\vartheta$  (electro-kinetic potential) show that the influence of the electrical field force is five to 15 times stronger than the effect of centrifugal force (with smaller particles, higher efficiency is achieved). For example, in the case of  $d=1 \mu\text{m}$  and

$\vartheta=0.3 \text{ V}$ ,  $F_C$  is  $0.026 \times 10^{-8} \text{ N}$ , while  $F_E$  is equal to  $0.225 \times 10^{-8} \text{ N}$  or more than eight times stronger than presented by Durst & Trautman (2005). Application of the particle precharging technique (as proposed by Ali-Zade *et al.* 1997) can further improve these parameters. The electric field can also help coagulate the organic substance, which would simplify the separation process. To realize the process, only 400–600 V is required on the main electrode. For this particular case, the effect of the magnetic force (estimated  $F_H=4.1 \times 10^{-10} \text{ N}$ ) on the organic emulsion is very insignificant and can be neglected.

## Application of EMHC for the textile dyeing industry

Textile manufacturing is a very important industry for many countries. Multicycle textile dyeing processes consume enormous amounts of fresh water. It is well known that the higher the purity of water, the higher the quality of the textile dyeing process. Commonly, in Turkey the textile dyeing facilities use mechanical multistage fine silk filters; however, their efficiency does not meet recent environmental protection standards set for the wastewater streams (with the main 'problematic' parameter being turbidity, which is currently set to a value of  $<10$ ).

There are more than 12 different operations performed during the textile dyeing process and each demands a new portion of quality water. Here, the recycled wastewater (after the proper filtration) can be used at least partially. It is relatively easy to separate rather large fibrous particles from wastewater, but removal of small impurities of  $50 \mu\text{m}$  and less (dust, organic contaminants, etc.) is extremely difficult. Therefore, it would be more appropriate to apply an effective electromagnetic separation process in order to reclaim the wastewater.

The pilot-type EMHC (Fig. 1) was designed according to the principles established by Ali-Zade *et al.* (1991, 1992, 1994, 1997) and duly tested. Owing to the nonmagnetic character of the textile dyes, the magnetic coil was not applied. The pump capacity was 5–6 L/s and the DC power supply was 100 and 200 V. Wastewater was taken from the waste channel (where it was disposed after the silk filters).

It is obvious that reliable filtration of the wastewater in a single pass through the EMHC is impossible. Therefore, purification was carried out in a closed cycle, i.e. partially purified water was returned back into a 30-L capacity initial tank (Fig. 1b) while the dye slime was gradually settling down in the cone and the bottom sides of the EMHC. In this way, treatment was realized within a 10-min period.

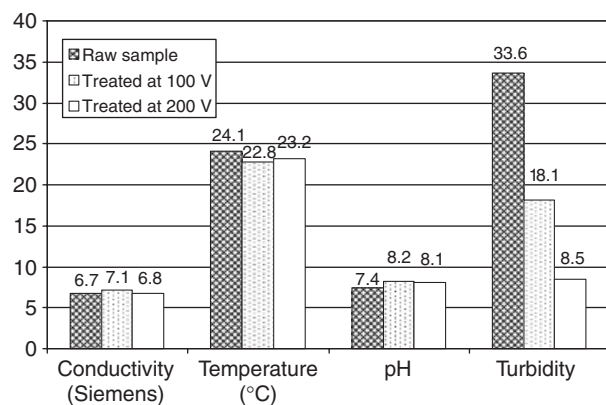


Fig. 2. Performance of electromagnetic hydrocyclone.

It was found that the application of a hydrocyclone alone (at  $V=0$ ) does not affect the turbidity: it remains at almost the same level of 32–33 (Fig. 2). After treatment with a DC voltage of 100 V, the conductivity and pH of the water were slightly increased. Turbidity was significantly reduced down to 18.1 and even further to 8.5 when a higher voltage, 200 V, was applied. Such a treatment does help meet the limits set by the standards (with a turbidity of  $<10$ ). The change in sample colour from dark brown to very light yellow was also observed.

## Concluding remarks

(1) The theoretical background and the design of EMHC were evaluated to focus on the purification of wastewater contaminated with particulate substances. The main factors responsible for the separation of small-sized impurities ( $<10\ \mu\text{m}$ ) are related to the application of electrical field, magnetic and centrifugal forces.

(2) The main advantages of the EMHC are as follows:

- The apparatus represents a hybrid system, which is designed to use electric and magnetic forces, along with centrifugal force, all of them aligned to act in the same direction.
- There are no rotating mechanical parts within the EMHC. Therefore, this type of EMHC can be implemented in high-pressure technological cycles.
- The separation process can be controlled by the applied voltage and current.

(3) The experimental tests demonstrated the efficiency of the developed apparatus in purifying the industrial wastewaters of the textile dyeing industry. The turbidity of contaminated process water was significantly reduced from 33.6 to 8.5 when a DC voltage of 200 V was used. The purification process was accompanied by a visible

change in sample colour from dark brown to very light yellow. Therefore, the treatment process realized with the developed EMHC provides purification to the limits set by the standards (at a turbidity of  $<10$ ).

(4) It is expected that the suggested process, in addition to a liquid–solid particle system, would be applicable for effective purification of other complex mixtures (such as liquid–liquid, liquid–gas, etc.). Examination of these treatment options, as well as EMHC in comparison with other purification techniques is left for future work. Future development should also explore the  $\text{O}_3$  formation option [when applying a high-frequency alternating current (AC)] to oxidize the residues of unwanted organic impurities, microorganisms and fungus.

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