Expert Systems with Applications 37 (2010) 7542–7551

Contents lists available at ScienceDirect

Expert Systems with Applications

journal homepage: www.elsevier.com/locate/eswa

The effects of fuzzy control of magnetic flux on magnetic filter performance and energy consumption

Ismail Saritas [a,*], Ilker Ali Ozkan [a], Saadetdin Herdem [b]

[a] Department of Electronic and Computer Education, Technical Education Faculty, Selcuk University, Turkey
[b] Department of Electrical and Electronics Engineering, Engineering and Architecture Faculty, Selcuk University, Turkey

ARTICLE INFO

Keywords:
Fuzzy control
Magnetic filters
Magnetic filters control

ABSTRACT

Magnetic filters are used effectively in many industrial areas to clean up technological liquids and gases from micron and submicron size magnetic particles. Performance of the magnetic filter is affected by technological parameters like flow rate of the industrial liquid and concentration and flux magnitude of the magnetic filter. These parameters exhibit differences depending on the field of work. Controlling of magnetic filters without regard to these parameters has disadvantages such as low filter performance, ineffectiveness in parameter changes and high energy consumption. To remove these disadvantages, an adaptive fuzzy control system which considers these technological parameters was designed and realized. When the realized filter is compared to the filter that ignores technological parameters, it is observed that energy can be saved at a rate of 68% annually.

1. Introduction

Magnetic Filters (MF) are used to clean magnetic particles from industrial liquids. It is important discharging the scraps and wear granules from the pipes through which the liquids flow (Abbasov & Ruzgar, 2005; Herdem, Abbasov, & Koksal, 2005), because, these particles may increase the pipe wear and cause very serious breakdowns.

MF's are preferred over other filtering techniques because they are not affected by high temperatures, can be used in many fields, do not harm the liquid to be cleaned, are economic and work efficiently. Consequently, use of MF has become widespread in recent years (Abbasov, 2002; Abbasov & Ceylan, 1999; Gerber & Lawson, 1994; Haitmann, 1969; Okada et al., 2002). They are used in many areas including food sector, medicine, woodwork, chemical industry and their field of use increases day by day.

Basic working scheme of MF is shown in Fig. 1 (Abbasov, 2007; Ozkan, Saritas, & Herdem, 2007; Saritas, 2008).

Depending on their fields of technology, performance of the MF in magnetic filtering is affected by many technological factors such as the flow rate, concentration, the size of the particles, magnetic attractiveness, liquid viscosity of the industrial liquid, and the non-magnetic particles inside the liquids. Additionally, MF magnetic body size and specifications, magnetic flux density, size of the magnetic filter matrix, physical and magnetic properties of the matrix elements also affect filter performance. Moreover, a difficult problem arises while cleaning the filters when the magnetic filter matrix pores cannot capture the particles. There are many studies in this area which are included in the relevant literature. Nevertheless, filter performance optimization and saving energy while doing this are among the problems still awaiting solution (Abbasov, 2007; Cueller & Alvaro, 1995; Gerber & Birss, 1983; Ozkan et al., 2007; Saritas, 2008; Saritas, Ozkan, & Herdem, 2007).

In this study, adaptive fuzzy control (AFC) is designed for optimization of magnetic filter performance. Magnetic flux of the MF is controlled by considering the liquid flow rate and concentration in the input. Also, the reaction of magnetic flux to technological parameters and its effect on energy consumption have been examined.

2. Design of experiment system

In this study, an experiment set in the Magnetic Filtration Laboratory (Fig. 2) of the Selcuk University, Engineering and Architecture Faculty has been used; the control process has been performed by using Labview software. Globules with a radius of 8–14 mm having magnetic properties have been used as filter matrix elements while suspensions prepared by mixing the pure water and iron powder having a size of 4–10 × 10^{-4} mm have been used as industrial liquid.

The system was built in Laboratory as shown Fig. 2.

In this system (Fig. 3), flow speed of the industrial liquid in the filter is measured with V_f. Input and output particle concentrations

---

* Corresponding author. Address: Selcuk University, Technical Education Faculty Campus, 42075 Selcuklu, Konya, Turkey. Tel.: +90 3322233354; fax: +90 3322412179.

E-mail address: isaritas@selcuk.edu.tr (I. Saritas).

0957-4174/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.eswa.2010.04.090

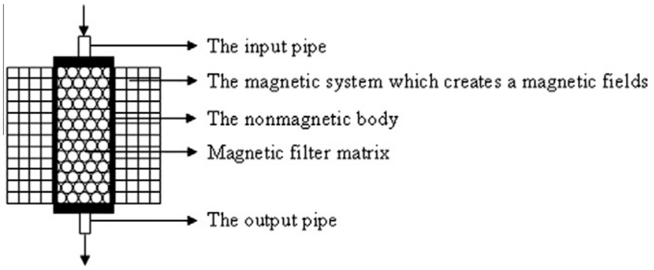


Fig. 1. The principle schema of MF.

are measured with S_1 and S_2 sensors. The suspension follows the route from the entrance through M_2–S_1–V_1–S_2 and the particles in it are captured in MF and directed to the cleaned liquid exit. Coil current, V_1–V_2 and M_1–M_2 are controlled according to the information coming from PC. When the procedure of regeneration of the filter has to be performed is determined with fuzzy control (FC) and it is ensured that this procedure takes place automatically.

The experiment system seen in Fig. 3 was designed with a filter matrix to clean industrial liquids, the required connections for its control and sensors and it was built (Fig. 2) and experiment system control was performed as shown in the chart in Fig. 4 (Saritas et al., 2007).

3. Fuzzy expert system

Fuzzy logic uses the mechanism of decision-making and reasoning without clear-cut boundaries used by humans instead of mechanical logic or absolute logic (Allahverdi, 2002). One of the most common applications that have arisen with the introduction of this concept is control mechanisms based on fuzzy logic. Fuzzy logic control systems do not require full knowledge of the system as in the case of the well-known PID control designs. This knowledge is replaced with the experience and mastery of the human being who is called the expert. An attempt is made to realize the fuzzy system by making use of expert knowledge and experience and the uncertain emotional data of the human being (Tsoukalas & Uhrig, 1997). Various design methods have been developed so far for this purpose and are still being developed (Etik, Allahverdi, Sert, & Saritas, 2009; Saritas, Ozkan, Allahverdi, & Argindogan, 2009; Wakami, Araki, & Nomura, 1993).

Basic structure for fuzzy control developed by using fuzzy logic is the fuzzy expert system (FES) mechanism (Fig. 5).

4. Magnetic filter control and programming

Various factors such as the dimensions of the MFs used in the cleaning of industrial liquids, the diameters of the spheres used in the filter matrices were investigated and calculations were made using empirical equation. There is ample research on this topic but studies regarding control of MFs are not at the desired level yet.

A filter was designed in this study and fuzzy control was considered to be the most appropriate artificial intelligence technique for this design, so the control system seen in Fig. 4 was developed.

Various factors are important for filter performance such as the flow speed of the industrial liquid that passes through the filter, the quantity of the magnetic particles in the liquid, the length of the filter and the filter matrix, the shape, size and magnetic property of the components in the filter matrix, magnetic property of the material from which the filter body is made, the type and number of spins of the filter coil and the current applied on the coil.

In this study, the control of the current passing through the filter coil using 14 mm radius filter matrix elements has been realized by using adaptive fuzzy control (AFC). Likewise, constant current has been passed through the filter coil under the same conditions and its effect on filter performance has been examined. Moreover, constant current filtration and AFC filtration have been compared in terms of their energy consumption.

In the fuzzy control, by virtue of the system in Fig. 4, the flow speed of the industrial liquid (V_f) and the concentration of

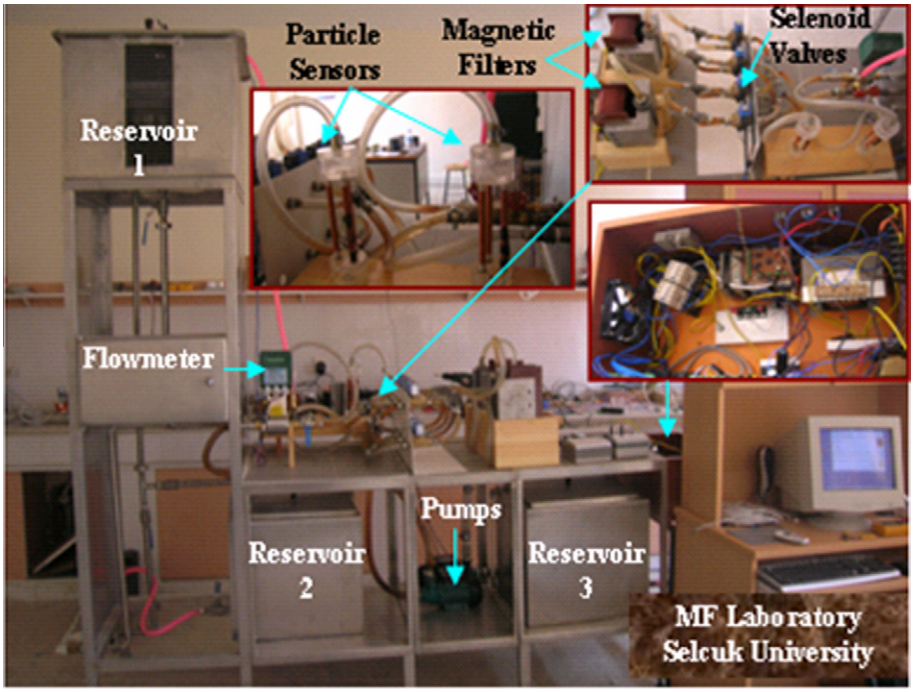
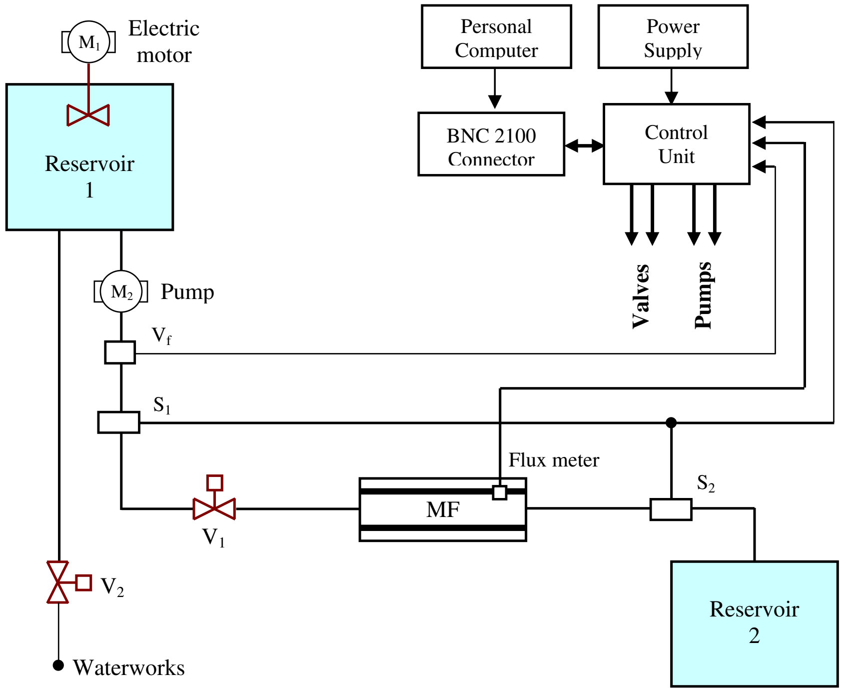


Fig. 2. Experiment System.



MF – Magnetic filter and matrix, V_1 and V_2-Valves, V_f– Flow meter, S_1 and S_2– Particle sensors

Fig. 3. Work principle of realized magnetic filter.

magnetic particles in the liquid (S_1) were selected as input parameters while the pulse-width modulation (PWM) reference voltage (U) was selected as the output parameter.

Linguistic expressions established for S_1, V_f and U are given in Table 1.

Triangle fuzzification was used for the linguistic expressions and the limit values are given in Table 1. Membership functions and membership degrees were defined in the Labview Fuzzy Control Toolkit software, which would be used for control. These values and their graph for the S_1 parameter are shown in Fig. 6. Similar membership degrees and functions were formed for other parameters (Figs. 7 and 8).

The rules established for the system are given in Fig. 9. An expert was consulted in establishing the rules.

Functions of the linguistic expressions of the input and output parameters were established using the Fuzzy Set Editor of the Labview Fuzzy Control Toolkit software while rule base was formed by using the Rulebase Editor of the same software.

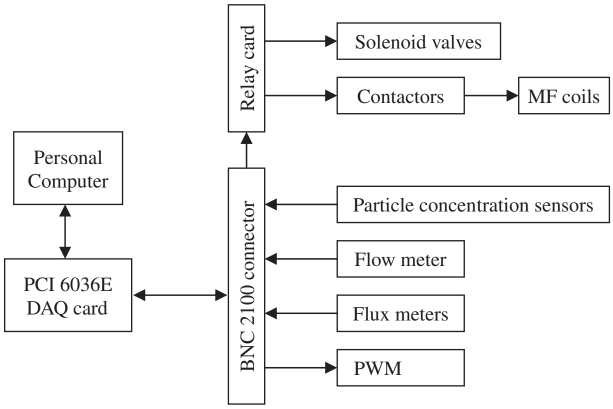


Fig. 4. Control units schema.

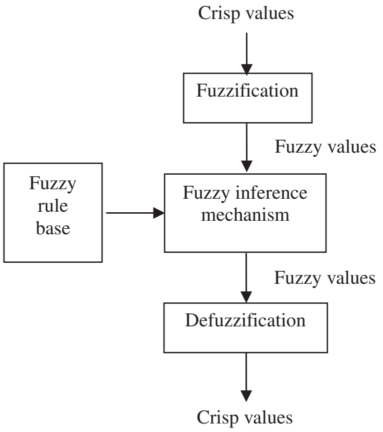


Fig. 5. Structure of fuzzy expert system.

As can be seen from Fig. 10, control is realized as both manual and automatic with Labview software.

Input and output units are programmed by using DAQ board and schematic diagram is given in Fig. 11.

In the designed system, experiments were performed by using filter matrix elements of 14 mm in radius for both constant magnetic flux and controlled magnetic flux, and suspension concentration and flow rates were changed in periods of 35 min during the experiment. During the experimental process, S_1, V_f, U and flux data captured in the sensors were transferred and saved on the computer.

Input and output concentrations obtained when 1A and 2A DC currents are applied on the MF coil and flow rate graphics of the

Table 1
Input–output parameters and linguistic expressions.

Input parameters Particle quantity (S_1 – mg/l)		Liquid flow speed (V_f – l/h)		Output parameter PWM reference voltage (U–V)	
Fewer	0–1.25	Slow	0–100	Lowest	0–0.25
Few	0–1.25–2.5	Lower normal	0–100–200	Lower	0–0.25–0.50
Medium	1.25–2.5–3.75	Normal	100–200–300	Low	0.25–0.50–0.75
Much	2.5–3.75–5	Upper normal	200–300–400	Lower medium	0.50–0.75–1
Much more	3.75–5	Fast	300–400–500	Medium	0.75–1–1.25
		Faster	400–500	Upper medium	1–1.25–1.50
				High	1.25–1.50–1.75
				Higher	1..50–1.75–2
				Highest	1.75-2

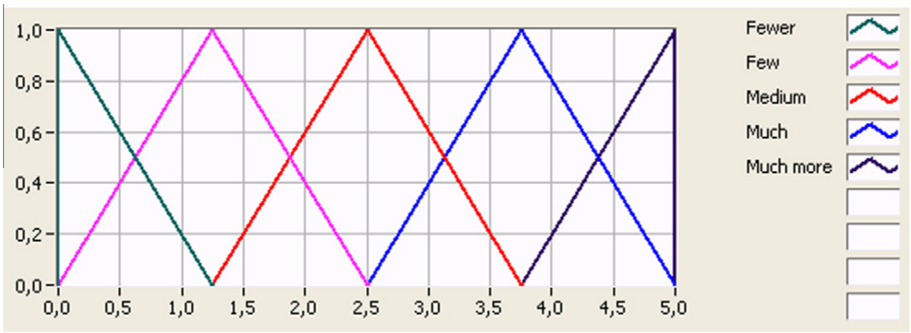


Fig. 6. Membership functions of particle concentration (S_1).

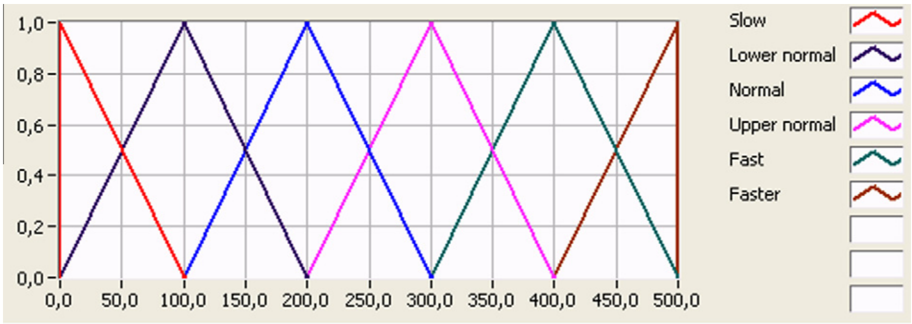


Fig. 7. Membership functions of industrial liquid speed (V_f).

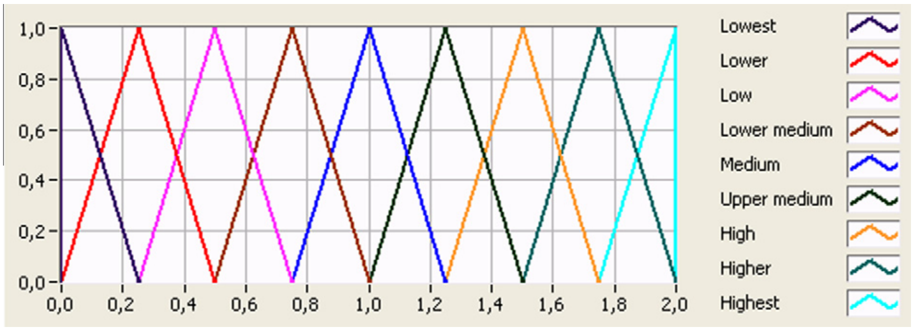


Fig. 8. Membership functions of PWM voltage reference (U).

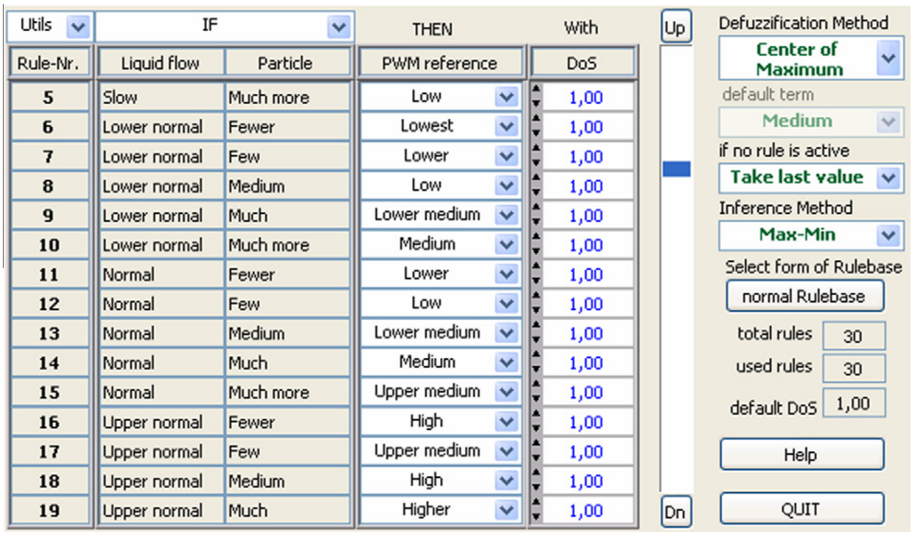
suspension are given in Figs. 12 and 13. A filtration is also performed by using AFC in the same the conditions as those of the constant current case. Input and output concentrations and flow rate graphics of the suspension when the AFC is used are given in the Figs. 14 and 15.

In AFC control experiments, current changes applied on the MF coil according to the input concentration value and suspension flow rate are given in Figs. 16 and 17 respectively.

5. Results and discussion

For each experiment, performances are calculated for each AFC controlled and uncontrolled case by using the experimental data. Eq. (1) is used for the performance calculations (Saritas, 2008).

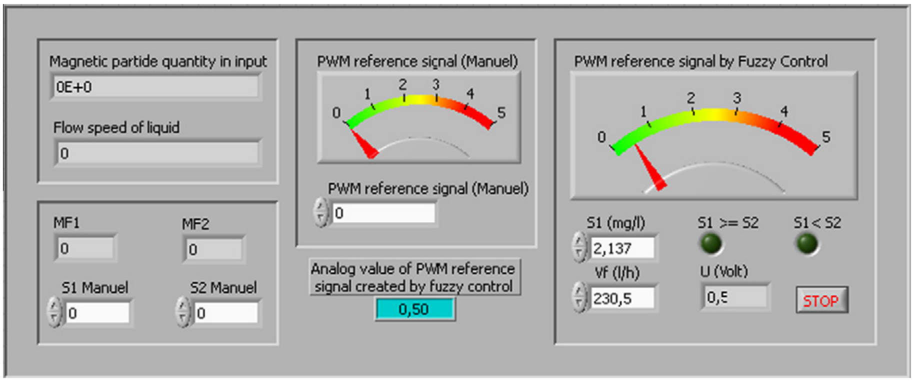
$$\text{MF performance } (\psi) = 1 - \frac{\text{MF output concentration value}}{\text{MF input concentration value}} \tag{1}$$



Utils	IF		THEN	With
Rule-Nr.	Liquid flow	Particle	PWM reference	DoS
5	Slow	Much more	Low	1,00
6	Lower normal	Fewer	Lowest	1,00
7	Lower normal	Few	Lower	1,00
8	Lower normal	Medium	Low	1,00
9	Lower normal	Much	Lower medium	1,00
10	Lower normal	Much more	Medium	1,00
11	Normal	Fewer	Lower	1,00
12	Normal	Few	Low	1,00
13	Normal	Medium	Lower medium	1,00
14	Normal	Much	Medium	1,00
15	Normal	Much more	Upper medium	1,00
16	Upper normal	Fewer	High	1,00
17	Upper normal	Few	Upper medium	1,00
18	Upper normal	Medium	High	1,00
19	Upper normal	Much	Higher	1,00

Defuzzification Method: Center of Maximum
default term: Medium
if no rule is active: Take last value
Inference Method: Max-Min
Select form of Rulebase: normal Rulebase
total rules: 30
used rules: 30
default DoS: 1,00

Fig. 9. Rulebase of AFC.



Magnetic partide quantity in input: 0E+0
Flow speed of liquid: 0
MF1: 0
MF2: 0
S1 Manuel: 0
S2 Manuel: 0
PWM reference signal (Manuel)
PWM reference signal (Manuel): 0
Analog value of PWM reference signal created by fuzzy control: 0,50
PWM reference signal by Fuzzy Control
S1 (mg/l): 2,137
S1 >= S2
S1 < S2
Vf (l/h): 230,5
U (Volt): 0,5

Fig. 10. The front panel in Labview of realized software in any time.

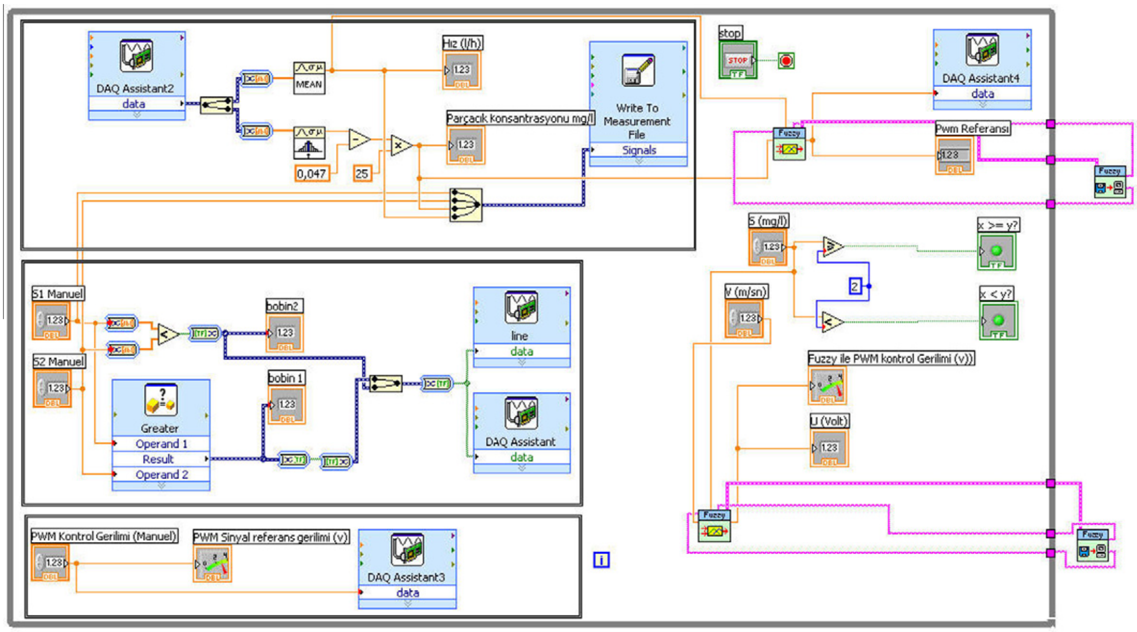


Fig. 11. The view of block diagram of realized software.

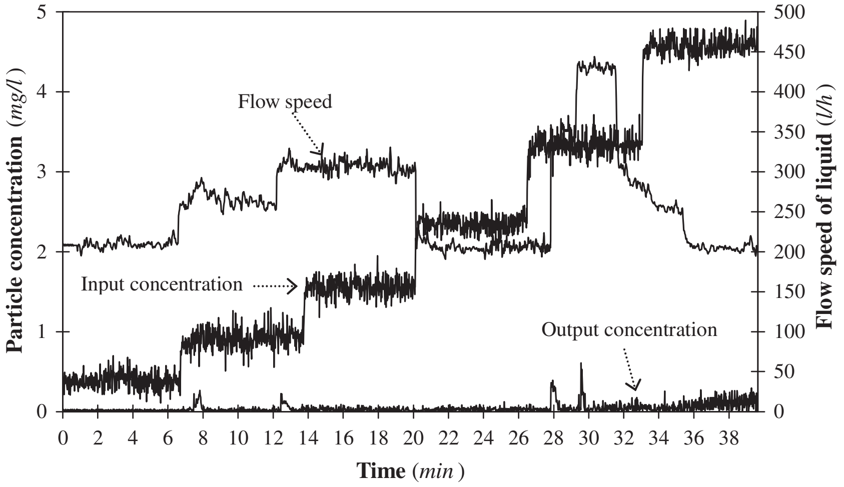


Fig. 12. Coil current constantly 1A, concentrations and flow speed of MF.

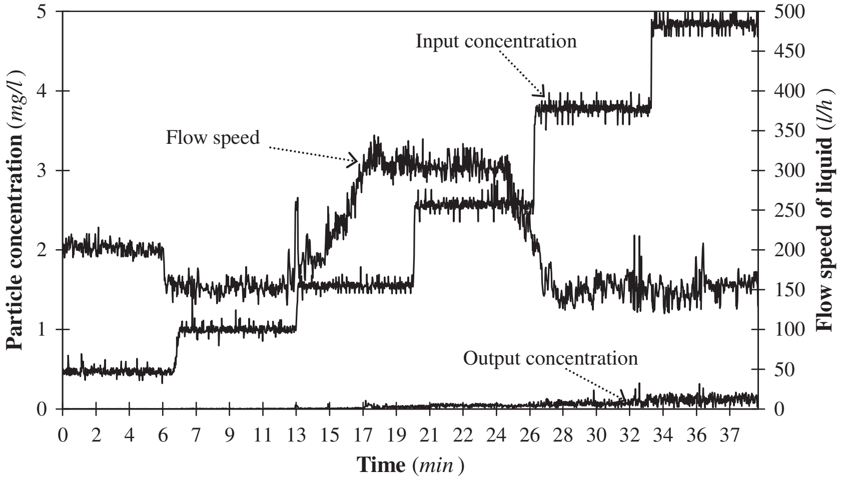


Fig. 13. Coil current constantly 2A, concentrations and flow speed of MF.

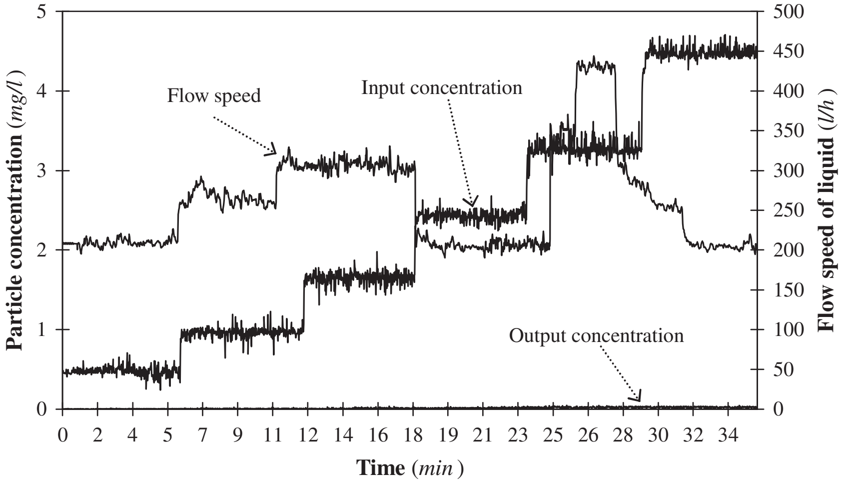


Fig. 14. AFC control for current 1A, concentrations and flow speed of MF.

MF performance values from Eq. (1) and currents applied to the coils are shown in Figs. 18–21.

In 1A constant current filtration, the particles captured in the filter matrix are separated from the matrix when the suspension

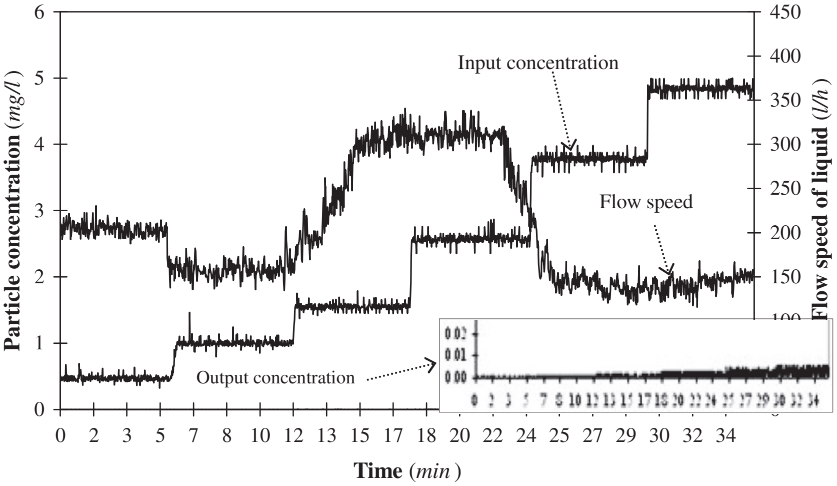


Fig. 15. AFC control for current 2A, concentrations and flow speed of MF.

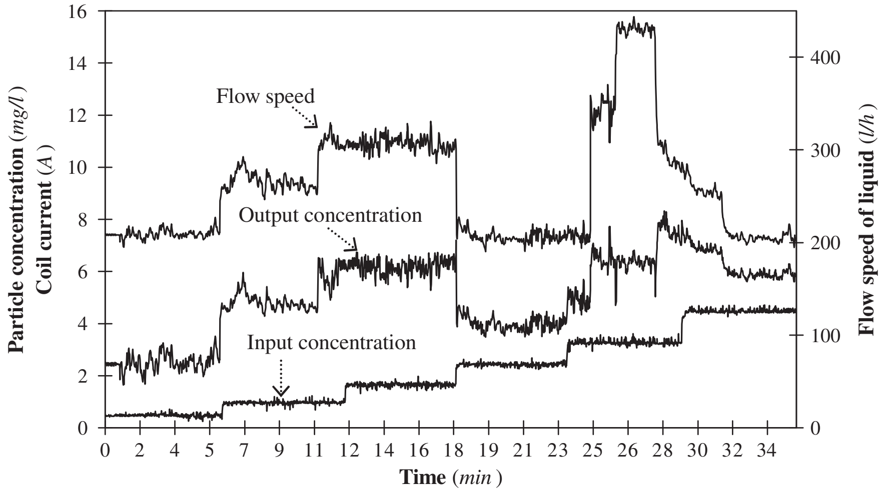


Fig. 16. The change of coil current depending on input concentration and flow speed.

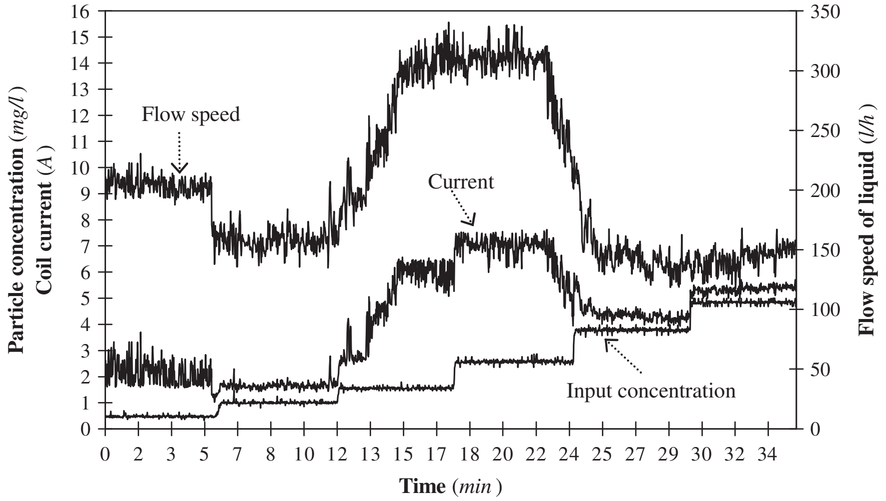


Fig. 17. The change of coil current depending on input concentration and flow speed.

flow rate increases. MF performance decreases in the aforementioned filtration case (Fig. 18).

It is seen in the experiment conducted with 2A constant current that there is less filtration in the filter matrix than in the 1A case

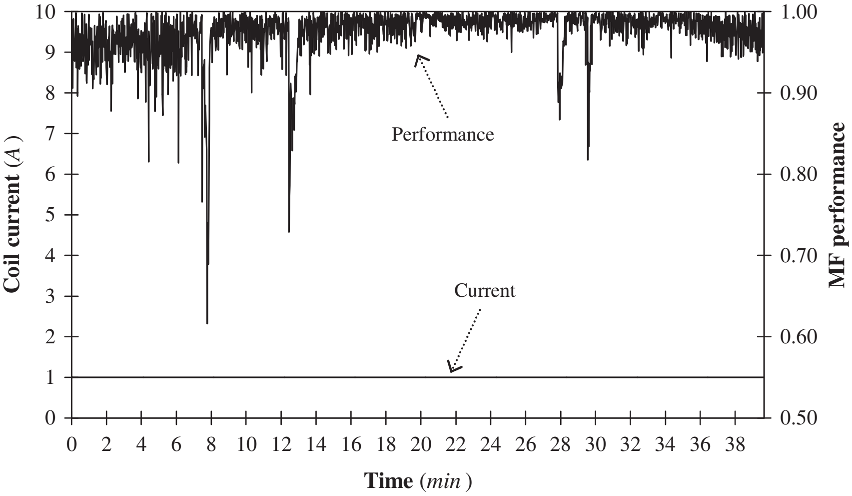


Fig. 18. MF performance and coil current in experiment 1.

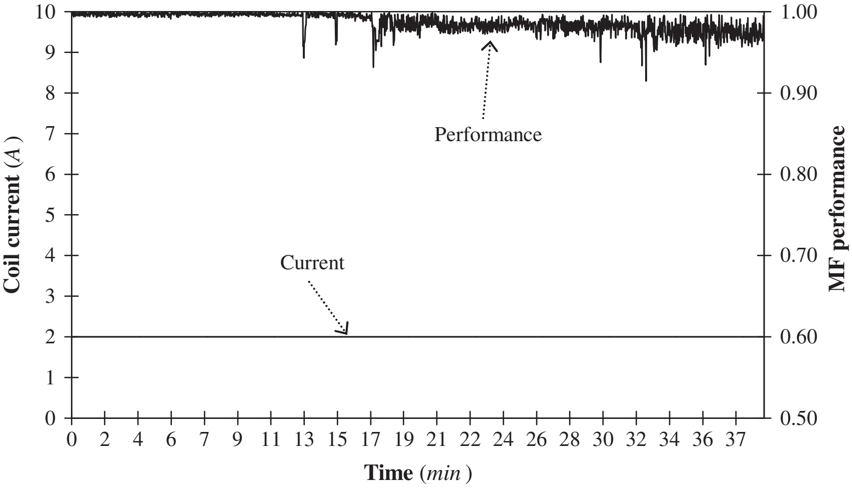


Fig. 19. MF performance and coil current in experiment 2.

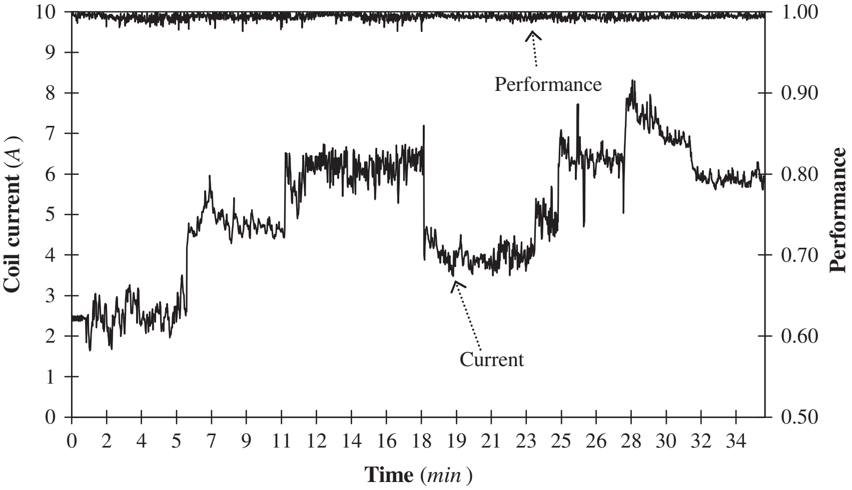


Fig. 20. MF performance and coil current in experiment 3.

when the speed of the suspension increases, but still there is a decrease in performance. (Fig. 19). An examination of Figs. 18 and 19 reveals that constant current case filtration process cannot respond to technological parameter changes and even if there is an increase

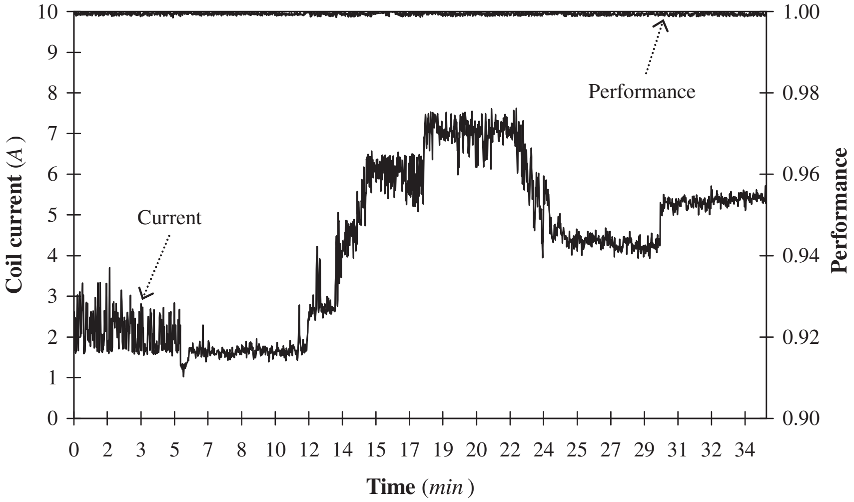


Fig. 21. MF performance and coil current in experiment 4.

Table 2
Energy consumption for the uncontrolled working of MF and AFC controlled cases.

Exp. no.	AFC controlled filtration					Uncontrolled filtration				
	U (V)	I (A)	P (kW)	Energy consumption		U (V)	I (A)	P (W)	Energy consumption	
				kWh/day	kWh /year				kWh/day	kWh /year
3	6.27	4.82	30.24	0.73	264.94	10.81	8.32	89.96	2.16	788.01
4	5.44	4.18	22.73	0.55	199.13	9.90	7.62	75.46	1.81	661.06

in the current, this disadvantage still continues. Parallel to these, MF performance also decreases.

MF performance obtained from AFC experiments is not affected by the suspension flow rate changes or particle concentration changes. It can be seen that depending on the suspension flow rate and particle concentration which affect MF performance, the current applied to the coil exhibits variation according to the PWM reference value (Figs. 20 and 21). Consequently, MF performance increases. Enough magnetic flux is provided to prevent filtration in magnetic filter matrix when there are sudden increases in flow rate or particle concentration.

Results of the experiments conducted using AFC control show that uncontrolled filtration should be performed with the highest coil current to get the same performance as with the AFC control. In this case, there will be energy losses, so calculations are made using the data obtained in the experiments.

In the 3rd and 4th experiments of the MF, in order to obtain the same power as in the AFC control, maximum current and maximum voltage values should be used in the uncontrolled case. Eq. (2) is used for these calculations.

$$P = \frac{U \times I}{1000} \tag{2}$$

In Eq. (2); P: power (kW), U: average value of coil voltage (V), I: average value of coil current (A).

Daily energy consumption of the MF and annual energy consumption are calculated by using Eqs. (3) and (4), respectively.

$$W_g = P \times t_g \tag{3}$$

$$W_y = W_g \times t_y \tag{4}$$

W_g is the daily energy consumption (kWh), W_y is the annual energy consumption (kWh), t_g is the daily working duration of the MF (h), t_y is the annual working duration of the MF (days).

Energy consumption of the AFC controlled MF is calculated by using Eq. (2)–(4) and given in Table 2. In accordance with these values, in the 3rd experiment 2.9743 times less and in the 4th experiment 3.3198 times less energy is consumed.

If the filter runs with AFC, optimum magnetic flux density is supplied to clean up the industrial liquid. Thus, not only is energy saved but also constant maximum filter performance is obtained at the same time.

In conclusion, filtration process with AFC provides more stable and reliable cleaning compared to the constant current case because of adjustment of magnetic flux resulting from the control of coil current in proportion to the industrial liquid flow rate and particle concentration.

In long periods of running, approximately 32% energy is consumed annually, and the remaining 68% energy is saved, which is very high economic gain.

Applying the MF's technological parameters adaptively on the coil current control optimizes the MF performance. In this case, stable and reliable filtration process is realized.

In this study, only two technological parameters which affect the MF performance are used. Some or all of the other ignored parameters could be used to obtain better results. The obtained results can contribute scientifically to better design, usage and modeling of the MFs and thus more useful methods can be developed.

Acknowledgements

This study has been supported by Selcuk University's Scientific Research Unit (Project number: 05401039).

References

Abbasov, T. (2002). *Process of electromagnetic filtering*. Ankara: Seckin Press.
Abbasov, T. (2007). Magnetic filtration with magnetized granular beds: Basic principles and filter performance. *China Particuology*, *5*(1–2), 71–83.

Abbasov, T., & Ruzgar, B. (2005). The method orientation targeted magnetic bearer in the high gradient fields. In *11th national congress of electric, electronic and computer engineering* (Vol. 1, pp. 99–101). Istanbul.

Abbasov, T., & Ceylan, K. (1999). Filter performance and velocity distribution relation in magnetic filtration of non-Newtonian liquids. *Separation Science and Technology, 34*(11), 2177–2189.

Allahverdi, N. (2002). *Expert systems. Expert systems and an artificial intelligent application (in Turkish)*. Istanbul: Atlas Press.

Cueller, J., & Alvaro, A. (1995). Fluid–solid mass transfer in magnetic filtration. *Separation Science and Technology, 30*(1), 141–151.

Etik, N., Allahverdi, N., Sert, I. U., & Saritas, I. (2009). Fuzzy expert system design for operating room air-condition control systems. *Expert Systems with Applications, 36*(6), 9753–9758.

Gerber, R., & Birss, R. R. (1983). *High gradient magnetic separation*. John Wiley.

Gerber, R., & Lawson, P. (1994). Magnetic cage filter. *IEEE Transactions on Magnetics, 30*, 4653–4655.

Haitmann, H. G. (1969). Iron oxides in boiled water removed magnetically. *Industrial Water Engineering*(12), 31–33.

Herdem, S., Abbasov, T., & Koksal, M. (2005). The particles, captured magnetic filter importance of magnetic susceptibility (in Turkish). In *11th National Congress of Electric, Electronic and Computer Engineering* (Vol. 1(20), 44–47). Istanbul.

Okada, H., Tada, T., Chiba, A., Mitsuhashi, K., Ohara, T., & Wada, H. (2002). High gradient magnetic separation for weakly magnetized fine particles. *IEEE Transactions on Applied Superconductivity, 12*, 967–970.

Ozkan, I.A., Saritas, I., & Herdem, S. (2007). It is modeling magnetic filtering process with ANFIS (in Turkish). In *Electric, electronic, computer, biomedical engineering 12th congress and exhibitions – EMO 2007* (pp. 415–418). Eskisehir.

Saritas, I. (2008). The design of magnetic filter for cleaning industrial liquids and adaptive control of filter by artificial intelligence methods. Ph.d. thesis, Selcuk University Institute of the Natural and Applied Sciences, Konya.

Saritas, I., Ozkan, I.A., & Herdem, S. (2007). Design of fuzzy expert system for magnetic filter performance according to magnetic field. In *5th international conference on electrical and electronics engineering – ELECO 2007* (pp. 401–405). Bursa.

Saritas, I., Ozkan, I. A., Allahverdi, N., & Argindogan, M. (2009). Determination of the drug dose by fuzzy expert system in treatment of chronic intestine inflammation. *Journal of Intelligent and Manufacturing, 20*(2), 169–176.

Tsoukalas, L. H., & Uhrig, R. E. (1997). *Fuzzy and neural approaches in engineering*. New York, USA: John Wiley & Sons, Inc..

Wakami, N., Araki, S., & Nomura, H. (1993). Recent applications of fuzzy logic to home appliances. In *Proceedings of the international conference on IECON '93, 15–19 November* (Vol. 1, pp. 155–160).