A SIMPLIFIED EMPIRICAL MODEL FOR THE ONE-STAGE DIRECT FILTRATION

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ABSTRACT

A new configuration of the one stage direct filtration process has been investigated by Prof. Fadel (correspondent author) and his team in Mansoura University, Egypt. In this configuration, deep media with fine gravel particles (size 2-4 mm) has been used under low filtration rate (5-8 $m^3/m^2/hr$). For this system a simplified empirical model is proposed to describe the one stage of direct filtration process under steady-state conditions. The model is obtained based on curve fitting of true field data, which is obtained from several plants employing direct filtration process. The model considers all the essential concepts that describe the two processes of flocculation and filtration in one tank and the competition between them for limiting depth. Further, the model has considered all the major factors, which affect on the filtration process such as filter depth, filtration rate, run length, run time, size of media, and alum dose. The present model has an explicit solution, which may be useful for many applications of such filters. The application of the model has been explained for a given set of data and verified by comparison with another filed scale data. Also using the present model, the optimum operation conditions for running this type of filter have been investigated. Compared with other solutions for such system, the model is simple, easy to use, and provides a quick tool for describing such system.

Key Words: Empirical model, Steady state, Coarse media, Potable water, Direct filtration, Single layer, One stage.

INTRODUCTION

Generally, conventional systems for water treatment may include flocculation, sedimentation and filtration processes. Recently, for low turbidity waters, elimination of the settling process and combining flocculation with filtration processes in one tank have been found to be advantageous. This combination is called “one-stage direct filtration process”. In this process, a suitable filter having single or multi-layers of media is used. Generally, this filter is running in down-flow conditions.

In several cases direct filtration using rapid sand filter may be of use for water treatment of low level turbidity. From this fact, a new direct filtration process has been investigated to the medium and high level of turbidity. In the new configuration, deep media with fine gravel particles (2-4 mm) has been used under low filtration rate (5-8 $m^3/\ m^2/hr$). Using this technique, more than 100 plants has been constructed and operated successfully through Egypt.

Several advantages can be realized when compared to the conventional systems. The advantages of this system may be summarized as follow.

- has low capital and running cost, Lose (1951) and Monscvitz (1978),
- easy to construct and to use, Foly (1967) and Hutchison (1977),
- requires minimum number and small size of the treatment units, thus occupies less surface area as compared to most conventional systems,
- requires less number of labor, facilities, and equipments, companied with the conventional systems.
- require less dose of chemicals and coagulants (Fadel 1989),
- has a reliable effluent with negligible algae problems (Fadel and Barakat, 2004; Fadel et al., 2004).
- can be applied for several types of water having low, medium, or high turbidity,
- can be washed by raw water with suitable period of ripening, and
- does not require periodical surface and cleaning, thus produces less amount of wastewater.

Despite the widespread use of the direct filtration process, few models are available for design and operation of such system. Modeling the direct filtration process seems to be very complicated due to the difficulty of simultaneous analysis of flocculation and filtration, which exist in one unit. Consequently, describing this system using any steady state models of flocculation and filtration principles, often yields, a set of algebraic and differential equations with no explicit solution, unless some assumptions are proposed.

At present, the one stage direct filtration process is designed using iterative procedure or by using a recommended number of surface loading associated with a desired removal efficiency. This recommended numbers are obtained from field experience or experimental results. Only few mathematical models are available for designing this system, in which mostly one or two operating parameters are considered under specific simplifying assumptions. For any water treatment method, it is unlikely that, one or two models will be of use to all researchers and designers. Rather, there should be a set of models, each designed for specific purpose (Bishop and Rittmann 1995). These models should be kept as simple as possible to answer the questions of interest.

This paper aims to deduce an empirical model to describe the direct filtration process of the one-stage, using single layer of uniform media. Using this model, computation of effluent turbidity (C) can be done after knowledge of influent turbidity (C_o), filter depth (d), surface loading (X), run time (r_t), run length (r_o), particle size of media (d_p), and alum dose concentration (A). After computation of C, other parameters such as filter efficiency and quantity of suspended solids captured inside the system can be obtained. Further, the quantity of washing water and thus washing time may be obtained. Deducing the present model can be explained in the following paragraphs.

DEVELOPMENT OF THE MODEL

A schematic of a typical direct filter running under steady state condition is shown in Fig. (1). The filter has a total depth d, particle size d_p, influent turbidity C_o, surface loading X, run length r_o, run time r_t, and alum dose concentration A. A typical filters of this type have been sited in several plants and have been run under different conditions of d, r_t, A, X, d_p, C_o, and temperature. All the important operational parameters as stated by Connick and Paul (1982) have been considered on the present model. The important locations at which these typical filters where found in Egypt are,

- Three plants were observed in **Kafr El shiekh** Governorate, which are located in Baklolah, Kelin, Sandela and Sarwah.
- Two plants were observed in **El Fayoum** Governorate, which are located in Sanouris and Bany Etman.
- One plant was observed in each governorate of **Damietta, El Menia, and Cairo**, which are located in El-Rahamnah, Maghagha, and Basous respectively.

According to data collected from these plants, the effect of d, X, r_o/r_t , d_p ,and A on the effluent turbidity (C) could be evaluated as follows.

(a) Effect of Filter Depth on the Removal Efficiency

It is will known that, the filter depth has a direct relation with the filter efficiency, i.e., increasing the filter depth will increase the filter efficiency. In the present case, Fig. (2) shows the effect of filter depth on the removal efficiency of the direct filter. The new investigation of the present case is that, when the filter depth is shorter than 0.4 m, no significant efficiency is observed. For filter depth ranging from 0.4 -0.8 m, a drastic increase is observed in the filter efficiency. For filter depth more than 0.8 m, moderate increase is observed in the removal efficiency. From Fig. (2), it is clear that the removal efficiency may reach 99.0 % when the filter depth reaches 1.2m according to the running conditions. From which, the maximum depth was taken as 1.25 m. With more increase in the filter depth, insignificant increase is obtained in the filter efficiency. At the optimum conditions of particle size, alum dose of 35.0 mg/L (liquid alum with 27 % conc.), run time of 20 hr, surface loading of 3.5 m/hr and temperature of 32 C°, the relation between the filter depth and the removal efficiency in the present case could be expressed as:

$$E\,(\%) = [\tanh (1.25d)^{3.0}]*100 \qquad \textbf{(1)}$$

Equation (1) has a correlation coefficient (r^2) of 0.92.

(b) Effect of Surface Loading on the Removal Efficiency

As shown in Fig. (3) the surface loading slowly affect the removal efficiency when X is less than 4 $m^3/m^2/h$. Increasing the surface loading up to 12 $m^3/m^2/hr$, the removal efficiency reaches to 23 %. With more increase in X, the removal efficiency comes down to less than 57%. At the optimum conditions of particle size of 4 mm, alum dose of 35.0 mg/L, run time of 20 hr, filter depth of 1.25 m and temperature of 32ºC, the relation between the surface loading and the removal efficiency in the present case could be expressed as:

$$E\,(\%) = [\,0.998^{X^{2.0}}\,]*100 \qquad \textbf{(2)}$$

where X is expressed in $m^3 / m^2/ hr$ Equ.(2) has a correlation coefficient (r^2) of 0.97.

(c) Effect of Particle Size of the Media on the Removal Efficiency

The particle size of the media plays the most important role on the filter efficiency. As found in literature, Chuang and Kun-Yan Li (1997) have confirmed that, there exist a high the effect of grain size on the performance of direct filtration. As shown in Fig. (4) the removal efficiency comes down to insignificant value at using particle of size 50 mm for the filter. In practice the particle size of 3-5 mm is recommended. However, at some cases of pre-treatment work, particle size greater than 5 mm may be of use. At the optimum condition of alum dose of 35 mg/L, filter depth of 1.25 m, surface loading of 3.5 m/hr, run time of 20 hr ..etc, the removal efficiency can be evaluated by using the following equation:

$$E\,(\%) = [1- \tanh (0.001\, d_p^{2.2})]*100 \qquad \textbf{(3)}$$

where d_p is expressed in mm. Equation (3) has a correlation coefficient (r^2) of 0.985.

(d) Effect of Alum Dose Concentration on the Removal Efficiency

In fact several factors may Govern the optimum dose of alum such as, turbidity level of raw water, surface loading, … etc. Chuang and Li (1997) have studied the effect of coagulant dosage on the performance of direct filtration, they stated that, there exist an optimum dose at which the filter produces high effluent efficiency. In the present study, liquid alum with a concentration of 27 % have been used. In our case as shown in Fig. (5), it is clear that the optimum alum dose may be found at concentration of 35 mg/L. Below or above this optimum concentration of alum, the removal efficiency comes down slightly from high level. Further, the one-stage direct filter may run without any alum dose to give removal efficiency about 60 %. At the optimum conditions of particle size of 4 mm, filter depth of 1.25 m, surface loading of 3.5 m/hr, run time of 20 hr and temperature of 32ºC, the relation between the surface loading and the removal efficiency in the present case could be expressed as:

$$E\,(\%) = [1 - 0.5*\tanh (0.8 -0.02\, A\,)^2] * 100 \qquad \textbf{(4)}$$

where the alum dose expressed in mg/L. Equation (4) has a correlation coefficient (r^2) of 0.99.

(e) Effect of Run Length on the Removal Efficiency

The final factor, which affects on the filter efficiency, is the running time relative to the beginning and the end of the washing time. When the run time is done after the washing immediately even by small time, low level efficiency is obtained. On the other hand, if the run time is conducted just before the washing time even by small value, high level efficiency is obtained. At the optimum conditions of particle size of 4 mm, alum dose of 35.0 mg/L (liquid alum with 27 % conc.), filter depth of 1.25 m, surface loading of 3.5 m/hr, the relation between the surface loading and the removal efficiency in the present case could be expressed as:

$$E\ (\%) = [\ 0.93 + 0.07\ r_t/r_o]\ *\ 100 \qquad \textbf{(5)}$$

where r_t, and r_o are expressed in hour. Equation (5) has a correlation coefficient (r^2) of 0.95.

(f) The Final Empirical Function

Combining equations (1), (2),(3), (4), and (5), the removal efficiency of the one stage direct filter may be obtained as:

$$\begin{aligned} E\ (\%) = & K_t\ [\ 0.998\ X^{2.0}\ ]\ *\ [\tanh\ (1.25d)^{3.0}]\ *\ [\ 0.93 + 0.07\ r_t/r_o]\ * \\ & [1 - \tanh\ (0.001\ dp^{2.2})]*[1 - 0.5*\tanh\ (0.8 - 0.02\ A\ )^2]\ *\ 100 \qquad \textbf{(6)} \end{aligned}$$

The above equation has a correlation coefficient (r^2) of 0.93 and K_t is a correction factor depending on the temperature and the local condition of the filter such as coagulant type, TSS, DS …etc. For the present case, the values for K_t has been determined as shown in Table (1).

Rearranging Equation (6), the effluent turbidity (C) of the roughing filter can be obtained from the following equation:

$$\begin{aligned} C = & C_o - K_t\ C_o\ [\ 0.998^{\ X\ 2.0}\ ]*[\tanh\ (1.25d)\ 3.0\ \ ]*[\ 0.93 + 0.07\ r_t/r_o]* \\ & [1 - \tanh\ (0.001\ dp^{2.2})]*[1 - 0.5*\tanh\ (0.8 - 0.02\ )^2] \qquad \textbf{(7)} \end{aligned}$$

The above equation has a correlation coefficient (r^2) of 0.88.

Table (1). The correction factor for different temperatures

Temperature °C	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**
Correction Factor (k_t)	0.995	1.025	1.035	1.045	1.055	1.06	1.065	1.07	1.07

MODEL RESTRICTIONS

It is clear that, the model has been deduced based on curve fitting of field data, so the model will be of use in the range at which the data were taken. The recommended conditions for applying the model are,

- turbidity level < 120.0 NTU
- total suspended solid < 100.0 mg/L
- dissolved salt < 2000 mg/L
- alum dose < 50 mg/L
- temperature < 50 ºC
- surface loading < 240 m^3/m^2/day
- particle size of media < 50 mm

EXAMPLE

Consider a specific raw water having the following characteristics:

Influent turbidity (Co) = 35.0 NTU
filter depth (d) = 1.2 m
run long (ro) = 24 h
run time (rt) = 12 h
alum dose (A) = 30 mg/L (liquid alum 27 %)
temp (T) = 30 ºC
surface loading (X) = 96 m^3/m^2/d = 4 m^3/m^2/hr
particle size of media (dp) = 5.0 mm

From Table (1) the correction factor for the above temperature is 1.055.

From Equation (6)

$$E\,\% = (1.06)(0.998)(0.965)(0.97)(0.98)(0.97)$$
$$E\,\% = 93\,\%$$
$$C = 35 - (0.93)(35) = 2.45 \text{ NTU}$$

It is useful to state that, the above data and result have been checked according to the field data from several plants, similar results from the field were obtained, but some plants have given effluent values less than the computed value. Average error of 20 % was recorded.

CONCLUSION

Empirical model has been developed to describe the one stage direct filtration process under steady state conditions. The model has considered all the important factors affecting the filter efficiency. These factors include, filter depth, particle size, surface loading, run length, run time, temperature, and alum dose concentration. Using this model, the complexity in evaluating the flocculation, and filtration parameters in limited depth has been eliminated. Further, the model has reduced the number of required variables and simplified the calculation steps. At the same time, the solution still considers the basic concepts that govern the simultaneous action of flocculation and filtration in one tank for limiting depth. The empirical model could be evaluated based on filed data conducted for a different operational parameters. The advantage of this model is the simplicity and explicit structure, which leads to quick computation and reduction of the computational efforts.

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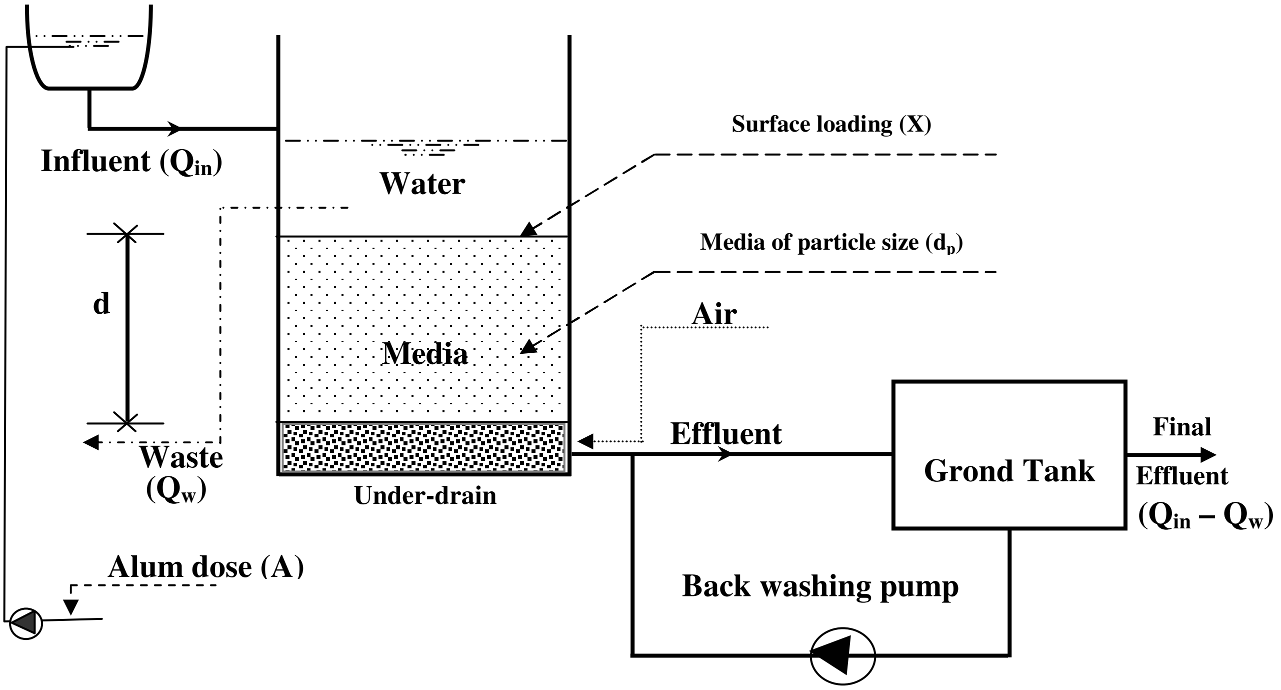

Fig. (1) Schematic diagram of one-stage direct filtration

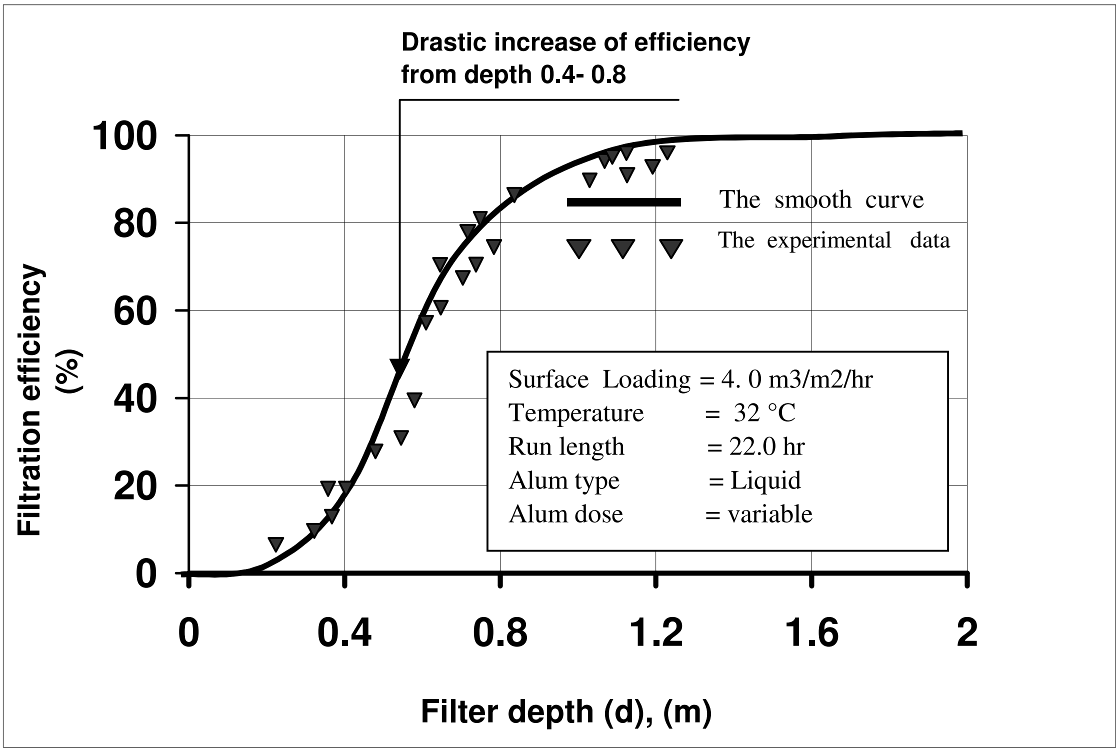

Fig. (2) The effect of filter depth on the one-stage direct filtration efficiency

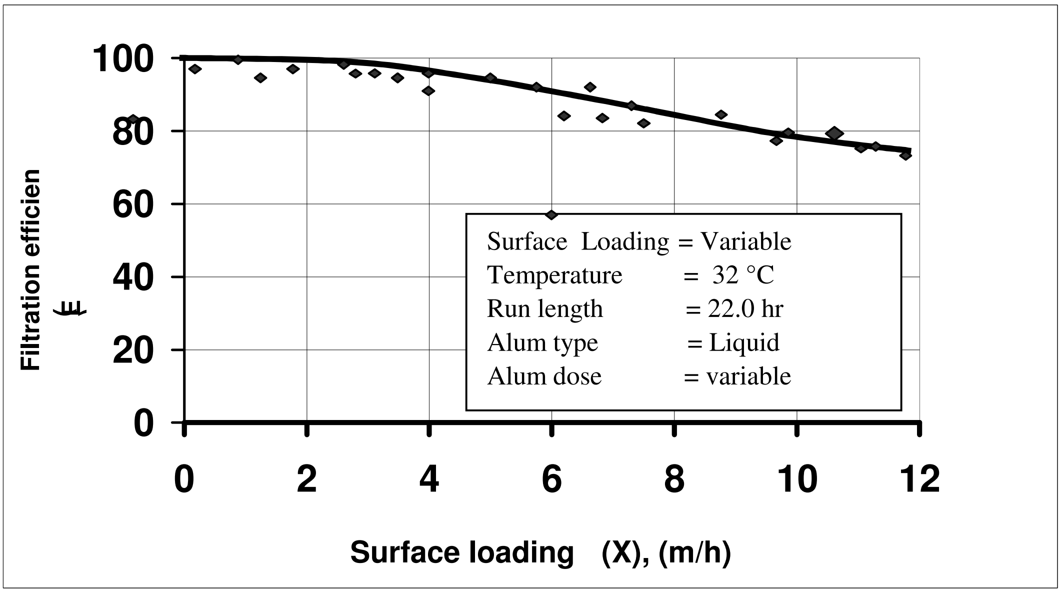

Fig. (3) The effect of surface loading on the one-stage direct filtration efficiency

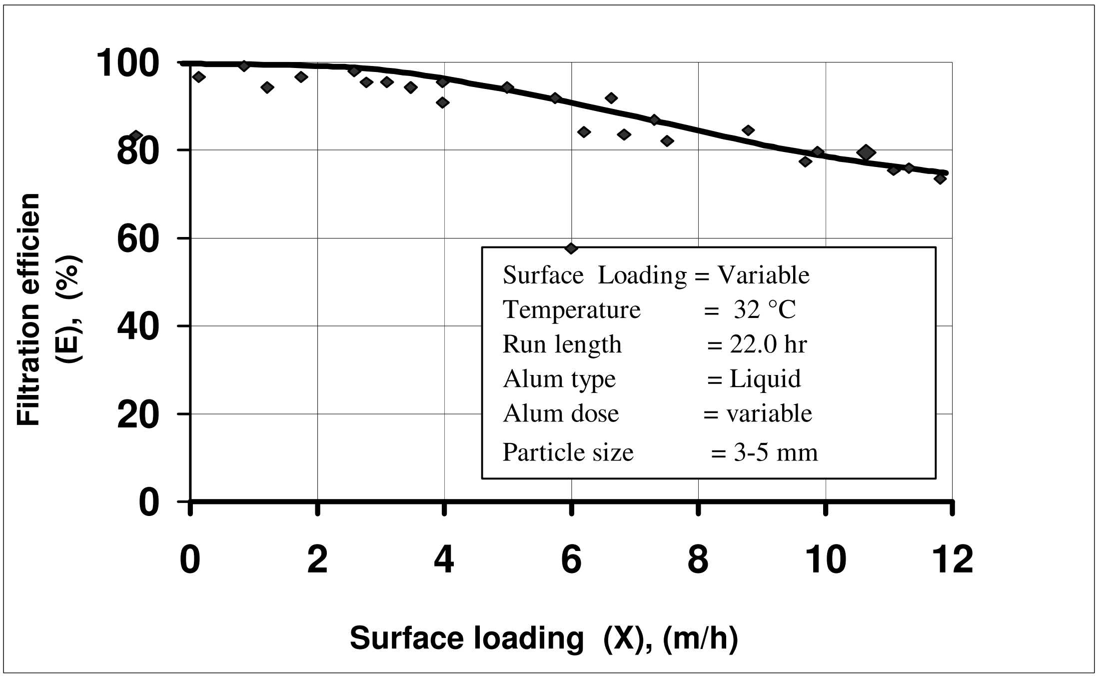

Fig. (4) The effect of particle size on the one-stage direct filtration efficiency

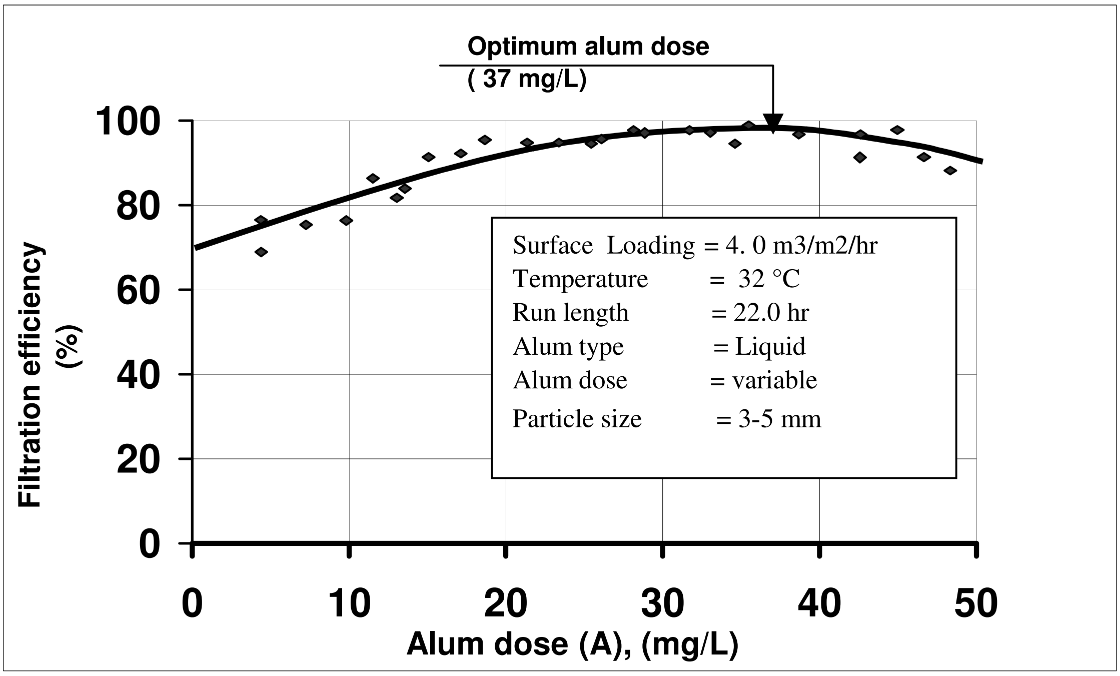

Fig. (5) The effect of liquid alum (27% Conc.) dose on the one-stage direct filtration efficiency

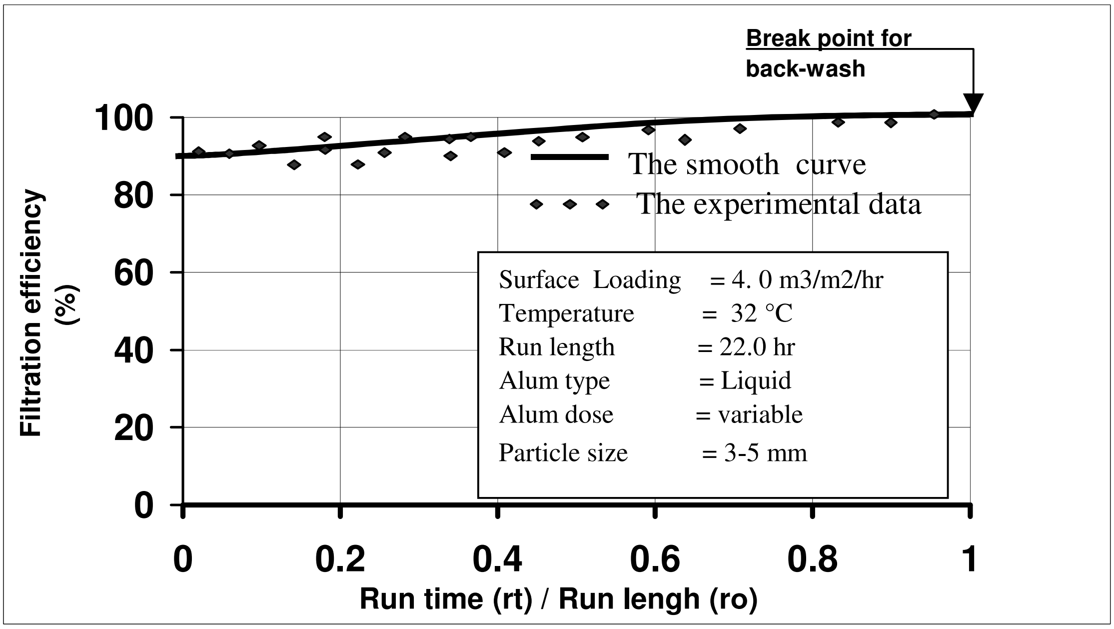

Fig. (6) The effect of run time on the one-stage direct filtration efficiency