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Disinfectant Filter Unit (DFU) in Water Treatment Plant

Ghassan Abukhanafer, Alaa H. Al-Fatlawi and Hasan Hamodi Joni
College of Engineering, University of Technology Civil Engineering - Sanitary and Environmental Engineering, Iraq

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Abstract:
This paperstudied the impact of the addition of pulse electric-filed infiltration process as a disinfectant function by designing, constructing, and operating a new laboratory-scale water filtration/disinfection technique. The Disinfectant Filter Unit (DFU) demonstrated several benefits in terms of efficiency, cost-effectiveness, and the ease of application, without the use of any chemical additive. This system contains a rapid sand filter and silver mesh electrode with a low pulse voltage for the water treatment. The parametric effects of the DFU performance, such as alternating current pulse frequency, the number of and the connection method of mesh electrode pairs, the voltage applied with electrical conductivity and electric field direction were studied. The exanimation of the cell wall morphology of Escherichia coli cells under transmission electron microscopy showed the change and damage before and after treatment. The optimum conditions were found to be 25 V, 0.5 Hz, and 2 pair mesh of electrode connection in an opposite direction of flow for 93% turbidity removal and 99.6% microorganisms removal

Keywords: *Filtration process, Pulse electric field, Escherichia coli, Turbidity, Disinfection.*

I. Introduction

After air, the next essential requirement for a human life is water. Water, more or less, contains excess chemical and biological compounds as well as pathogens which must be eliminated before consumption. The mechanisms of particle removal can be classified as gravity separation (i.e., sedimentation or flotation) and filtration [1-3]. To enhance the removal efficiency, chemical additives (e.g., iron or aluminum salts and polymers) are widely utilized to eliminate the negative charges carried by particles in the nature. After charge neutralization, these particles can attach to each other or to other surfaces to form larger settleable particles called flocs, which settle down and are removed during the water filtration process [4-6].The filtration concept is quite simple. The influent water passes through a granular sand layer (or other filter media) onto which the particles are captured by the media and the water exits as effluent with only a fewer particles. The prime removal of small particles is achieved in the filtration process, especially for parasites and pathogens. The chemical additives enhance particle-removal efficiency; however, they also increase the volume of residual solids that are formed as a byproduct of the treatment process. The landfill expense of residuals disposal amounts to millions of dollars every year for the water treatment industry [7-9].

It is therefore necessary to search for advanced techniques to enhance the efficiency of particulate removal in the process of treating drinking water while simultaneously reducing the dose of chemical additives, avoiding byproduct formation, residual toxicity of the effluent and, thereby, decreasing the cost of chemicals. Disinfectant filter unit (DFU) is a possible alternative process to this, which involves the use of low-voltage pulse applied external to the electrical field within the filtration process so as to enhance the particle removal (filtration) process as well as to inactivate the microorganisms contained in the water (i.e., the disinfection process)

Filtration is a process that removes particles from suspension in water. Removal takes place by several mechanisms that include straining, flocculation, sedimentation, and surface capture. Filters can be categorized by the primary method of capture, (exclusion of particles at the surface of the filter media) straining, or deposition within the media (in-depth filtration)[10-12].

The use of water disinfection as a public health measure reduces the spread of diseases. Various disinfection technologies can be used to achieve pathogen inactivation. Many of these chemical disinfectants, if overdosed or

March - April 2020
ISSN: 0193-4120 Page No. 11187 - 11194

misused, can react with the organic and inorganic precursors in the water and lead to the formation of disinfection byproducts (DBPs) with adverse health effects, and the other methods such as ozonation and ultraviolet (UV) radiation are expensive. Drinking water regulations require that drinking water treatment plants must be equipped with a disinfection phase when the surface water is used [13-15].

The application of the electric field on particle removal is widely applied in the air–particle systems such as electrostatic precipitators (ESPs). However, in the liquid–particle system, this system has received much less attention, probably because of the higher viscosity of water and the limitation in applying a different range of voltage in the water media [16, 17].This study investigated the new trend of using a DFU in drinking water treatment plants to enhance the effectiveness of the conventional treatment methods such as filtration and disinfection. The effect of various experimental variables, including alternating current (AC) pulse frequency, voltage, number of and connection method of mesh electrodes pair, and electric field direction were examined to identify the suitable conditions for optimizing the DFU-LV performance.

II. MATERIALS AND METHODS

Disinfectant filter unit (DFU)

The DFU consists of 3 layers of sand, fine gravel, and coarse gravel from the top to the bottom, respectively. These media are similar to those used in the filtration unit of the water treatment plant in Iraq. Table 1 shows the grading and layer thickness of the media, while the physical and chemical characteristics of the media used in the pilot-scale plant are summarized in Table 2.

Table 1. The grading of media and layer thickness

Depth (mm)	Media layers(mm)
Gravel size (mm)	
15	2.5-6.5
15	6.5-9.5
10	9.5-13.5
10	13.5-38
Sand layer (mm)	
70	0.6-1

Table 2. The characteristics of physical and chemical of the sand (size 0.6-1mm).

Sand of (0.6-1)mm	Iraqi Specification No.1555 on the year 2000 and it's modifications
D_{10}= 0.61	(0.6-0.65) mm
UC = 1.24	1.5 maximum
Solubility in HCl acid = 1.42	2% maximum limit
Content of SO_3 = 0.7	1% maximum limit
Content of clays = 0.25	Not more than 2%
Granular density = 2580	(2500-2670) kg/m^3
Silica = 91.9	Not less than 90%
Porosity = 40%	Shape = Rounded semispherical

Two or four silver mesh electrodes of approximately 1.35-m length/unit were placed in the column test above the filter media at a different distance between them. The mesh electrodes, power supply, voltage change control, and pulse frequency device were all connected. The polyvinyl chloride (PVC) column test had a diameter of 0.15 m, height of 3 m, and a cross-section area of 0.0176 m2. The material of the inlet and outlet pipe was also PVC with the diameters of 0.0125 and 0.0375 m, respectively. The water pump had the characteristics flow rate of 10-30 L/min, head space of 4-30 m, and the maximum liquid temperature of 40 ± 1°C.

Microbiological cultivation

For the case of urinary tract infections (UTIs), chromogenic agar was prepared by suspending 47.5 g of the media in 1 L of distilled water. The mixture was mixed well and the agar was dissolved by heating with frequent agitation. Then, the mixture was boiled for 1 min until complete dissolution. [18-20]. The resulting media was sterilized by autoclaving at 121°C for 15 min, followed by cooling to 45-50°C (Fig. 1 a), mixing well, dispensing into plates, and leaving them to solidify. The dehydrated medium was homogenous, free-flowing, and beige in color (Figs. 1 b and c).

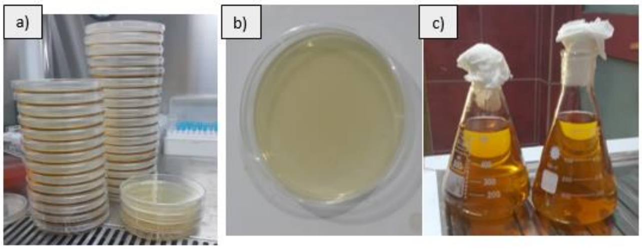

Fig. 1. UTI media preparation.

Experimental setup

A pilot-scale of the DFU was designed and constructed to simulate the filtration and disinfection processes of the conventional water treatment plant (Fig. 2). A water tank of 400 L was set beside the system and used as the reservoir. The influent flow rate was controlled by the flow meter between the water tank and the column test. The influent water was the raw water from the Al Hilla river. The height of water 1.5-m above the filter media was set to maintain a constant head. First, the influent water was passed and disinfected through the column test between the mesh electrodes by pulse electrical field. The mesh electrodes were alternatively connected to the positive and negative output of the power supply. Voltage change control (0-30 V) was used for controlling the applied voltage along with a pulsed electric device with a different mode of frequency. Second, the water effluent was filtered by media, where the particles were captured. The filtered water was then passed through a flow meter, which measured the flow rate to the treatment tank. The DFU was backwashed for 10 min by using tap water after each run to remove the captured particles.

Mechanisms of DFU

This paper is based on the conventional filtration process in water treatment plants by using the pilot plant. The rapid sand filter was used with/without electric pulse field of the low voltage applied. In the DFU process, the primary mechanisms of particle deposition in the media included inertial impaction, interception, gravitational settling, and electrostatic attraction [21, 22].In the absence of the electric field, the particles entrained and captured in this media due to the short-range van der Waals forces. In the water phase, most of the natural particles, including biological colloids, carry some negative surface charge. Similar to the effect of the gravity field on applying, the electric pulse-field with low voltage (PEF-LV) in the filtration proses increased the probability of particle deposition on the electrode surface and between the sand media by the additional migration velocity of these charged particles (Fig. 3). Unlike in the conventional flocculation process, charge neutralization is not necessary to enhance the particle-removal efficiency in the DFU process. Therefore, the dosage of chemical additives can be minimized to reduce the generation of residuals; thereby, decreasing the cost of chemicals and waste disposal. In addition, the PEF-LV works holes, then rupture the external wall of the microbial cell, leading to the leakage of the inner contents and resulting in the death of the pathogenic microorganisms. The pathogenic cells get destroyed, resulting in the reduction of the growth and reproduction of the microbes contributing to the infection.

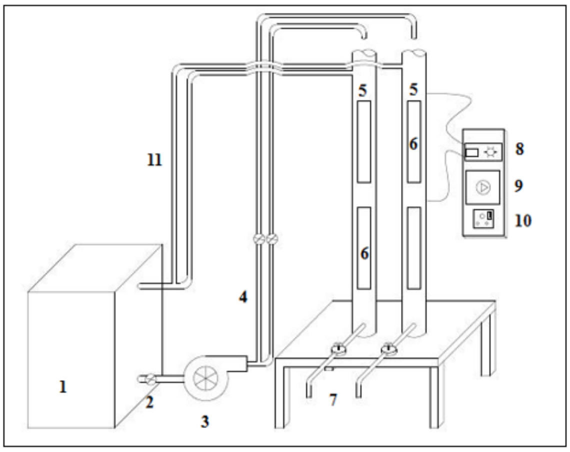

Fig.2. schematic of the pilot-scale DFU setup 1) tank of raw water, 2) valve, 3) pump, 4) influent PVC pipe, 5) column test, 6) glass, 7) effluent PVC pipe 8) voltage control change, 9) pulse frequency device, 10) point of power supply,11) effluent of raw water.

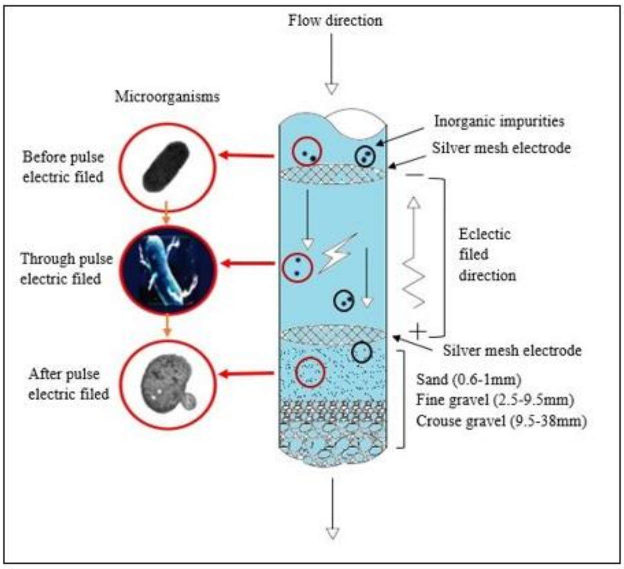

Fig. 3. Mechanisms of Disinfectant Filter Unit, (DFU).

March - April 2020
ISSN: 0193-4120 Page No. 11187 - 11194

III. RESULTS AND DISCUSSION

In this paper, several parameters such as i) the effect of the operation parameters, including AC pulse frequency, the applied voltage, the numbers and connection method of mesh electrodes pair, and electric field direction were investigated. influent

Effect of alternating current pulse frequency

AC frequency is the number of pulse per second in an AC sine wave. Frequency is the rate at which the current changes the direction in a second, and it is measured in hertz (Hz)[23]. The effect of pulse frequency changing from 0.5 to 2 Hz to DFU performance at different applied voltages (0-30 V) with a pair of silver electrode mesh was tested. Fig. 4 demonstrates that the increasing pulse frequency provides a higher microorganism efficiency removal. This result is consistent with that of past researchers [24, 25]. At the frequency of 0.5, 1, and 2 Hz, the corresponding exposure time was 2, 1, and 0.5 s. Therefore, 0.5 HZ was selected as the optimal frequency that gave an E. coli-removal efficiency of 93.5%. The increase in the frequency increased the number of pulses applied to the microbial cell. The amount of time for which a bacteria cell was exposed also increased according to the Planck's formula (Eq. 1)[26].

$$\text{Frequency} = \frac{1}{\text{Time (s)}} \quad (1).$$

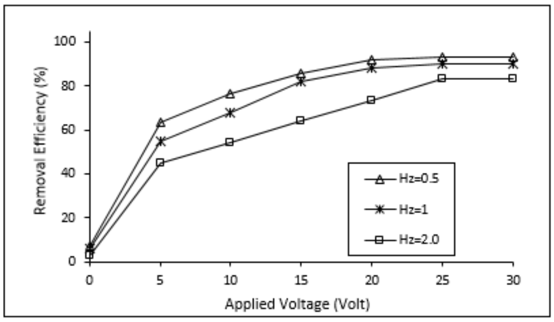

Fig.4. the effect of Alternating current pulse frequency on the removal efficiency of E-coli

The effect of enumeration of mesh electrodes pair and connection method

As mentioned earlier, at 1 pair of silver mesh electrodes, the E. coli-removal efficiency was 93.5%; therefore, this section will discuss the effect of the number of electrode mesh with the corresponding DFU performance. The effective disinfection area is proportional to the number of mesh electrode pairs and the connection methods. When the number of mesh electrode pairs increases, the effective disinfection area also increases, as per the following equation [27]:

$$\text{Effective disinfection area} = \left[\left(2 \times n - 1 \right) \times A \right] (2)$$

Where, n is the number of mesh electrode pairs and A is the area of the mesh electrode (cm2). The effective electrode area was 308 cm2 and 616 cm2 when single and double pairs of mesh electrodes were used, respectively. The retention time of microorganisms between the mesh electrodes increased when the number of electrode pairs increased. Hence, the time for which the cells were exposed to the electrical field was longer, which yielded better performance [28, 29] the increase in the number of electrode pairs in continuous flow treatment can help to enhance the pulse electric field performance.

Two methods of connecting electrodes i) all the electrodes in connected series, the electrode and electric field area is larger, As a result, two pairs of electrodes can result in having three electric field areas for disinfection, the removal efficiency was 99.6% (Fig.5). However, ii) the electrodes were connected separately; the electric field area is limited to one side of the electrode, and therefore a relatively smaller electrode and electric field area, and the removal efficiency was 95.1% (Fig.6).So the series method with the opposite electric filed direction of water flow was adopted in this study.

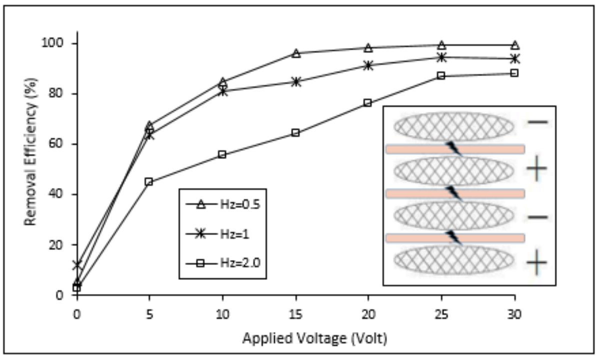

Fig. 5 The effect of the number of mesh electrodes pairs on the removal efficiency of E-coli.

with a series connection method , electric field area meshes electrodes.

March - April 2020
ISSN: 0193-4120 Page No. 11187 - 11194

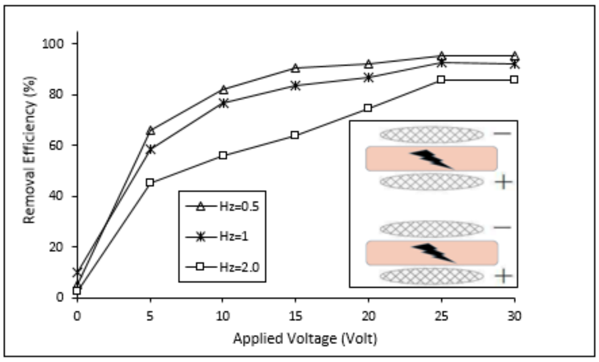

Fig. 6. The effect of the number of mesh electrodes pairs on the removal efficiency of E-coli. withseparate connection method , electric field area mesh electrodes.

Effect of the applied voltage

Voltage is the pressure from an electrical circuit's power source that pushes charged electrons (current) through a conducting loop, and it is measured in volts (V). The applied voltage plays an important role in DFU performance, as it is the main contributing factor to the applied electric field strength [25-27]. From an economic perspective and safety concerns, the voltage used was ranged from 0 to 30 V at the pulse frequency of 0.5 HZ and electrical conductivity of 250-1250 µs/cm. As mentioned earlier, increasing the applied voltage yielded a better removal efficiency of the microorganisms. These results are consistent with those of other researchers [28-33]. At 0-30 V, 0.5 Hz, 2 pairs of mesh electrodes, and opposite electric field direction of water flow, the best removal efficiency of E. coli was 99.6% at 25 V of applied voltage.

The removal efficiency of E. coli increases with increasing magnitude of electrical conductivity, because it measures the ability to allow the transport of an electric charge [34]. For this reason, the effect of electrical conductivity on DFU performance was investigated in this study. At the electrical conductivity of 250-500 µs/cm, the removal efficiency was <60%, at 501-900 was about 85 %, while that at 901-1250 µs/cm, it was 99.6% at 25 V, as depicted in Fig. 7.

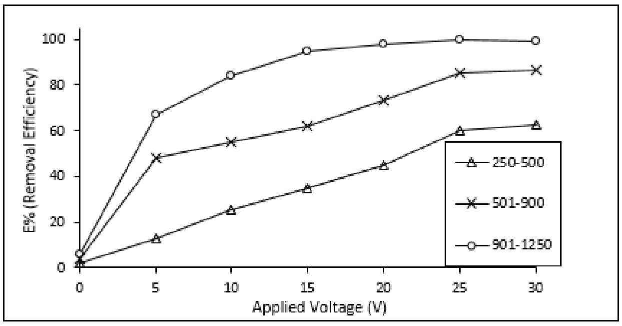

Fig.7. The effect of the electrical conductivity to the removal efficiency of E-coli.

To demonstrate the above mentioned result, this paper used transmission electron microscopy (TEM) micrographs of E. coli cells. Fig. 8 displays the change in the cell wall morphology before the treatment (it was a normal cell shape with an undamaged structure of inner and intact outer membrane) and that after the treatment by PEF-LV (0-25 V), which was peptide-induced breakage and roughness in the cell wall. Increasing damage to the bacterial cellwall was evident in the form of cracks developed by increasing voltage. Cell shrinkage due to the loss of turgor was also noted.

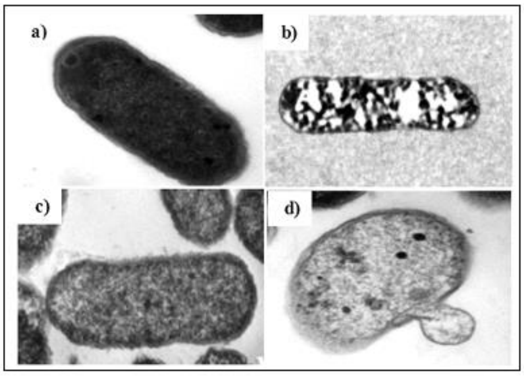

Fig.8. TEM micrograph of Escherichia coli (a) untreated cell, (b and c) treated cell with exposure to pulse voltage 10-20V (d) rupture the cell wall under 25-30V.

Effect of electric field direction

Two directions of the electric field were applied to the water flow in DFU. The parallel direction of the electric field to the water flow was the first direction. The resultant force (F net parallel) exerted on the bacteria cell was obtained from two forces: that exerted to the bacteria cellwall by water flow (Fw) and that exerted to the bacterial cellwall by an electric field (FEF). While the resultant force (F net opposite) exerted to the bacteria cell was also obtained from two forces: force exerted to the bacteria cell wall by water flow (Fw) and that exerted to the bacteria cell wall by electric field (-F EF) in an opposite direction to that of the electric field induced by water flow. Therefore, F net parallel > F net opposite, and by Newton's third law of motion, the following equation was obtained (Eq. 3) [32, 35, 36]

$$F_{net} = \frac{m \times v - m \times u}{t} \quad (3)$$

Where, m is the mass of the bacteria cell, v is the velocity of water, u is the initial velocity of water, and t is the time needed by the bacterial cell to travel through the electrodes. Since the mass of the bacteria cell and the velocity of water remained unchanged, the Equation 3 can be simplified to the following.

$$\text{Fnet} = \frac{m \times v}{t} \quad (4)$$

According to Eq. 4, the force of a bacteria cell exerted was inversely proportional to the time for which a bacteria cell traveled in the electrodes. The resultant force that the bacteria experienced was smaller when the electric field direction was opposite to that of the water flow, the time needed for the bacteria cell to travel in the electrode was longer; the time for which the bacteria cell was exposed to the electric field was longer; and, hence, the bactericidal performance was relatively better. Fig. 9 indicates that the removal efficiency of bacteria of 99.5% was achieved at applying the opposite direction of the electric field, while 84.5% removal efficiency of microorganisms was achieved when the flow direction was parallel to the water flow.

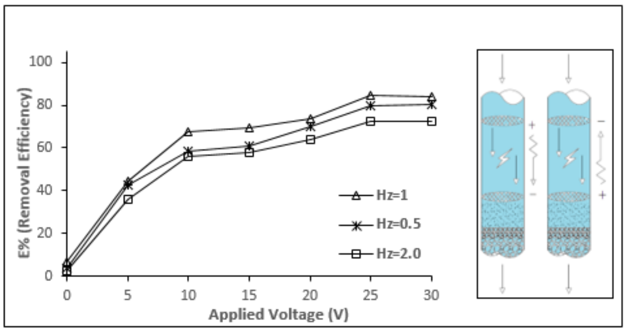

Fig. 9. The effect of the electric field direction on the removal efficiency of E-coli.

flow direction electric filed diction

This paper presents a new trend (DFU) that can be used for drinking water treatment plants to improve the conventional treatment methods of filtration and disinfection. The pilot-scale system utilized a rapid sand media as a filtrating function and silver electrode mesh with a low voltage as a disinfectant function. DFU was affected by several parameters such as AC pulse frequency, the applied voltage, number, and connection method of mesh electrodes pair and electric field direction. When the experiments were performed under optimal conditions (25 V, 0.5 Hz, and 2 pair mesh of electrode connection in an opposite direction), it became evident that >99.6% and 97% E. coli-efficiency removal and turbidity, respectively. The proposed system showed that the best conditions ensured the rupture of E. coli cell wall under the voltage of 25-30 V.

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March - April 2020
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