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Optimal design parameters for hydraulic vertical flocculation in the package surface water treatment plant

Key words: hydraulic flocculator, vertical flocculator, package water treatment plant, velocity gradient, detention time, baffle

Introduction

The issue of water in general and potable water in particular is of the highest interest and that the provision of potable water to all citizens in all areas and villages in Iraq requires the availability of several factors, the most important of which is the provision of water and electricity sources and the provision of financial allocations and land for the establishment of water stations.

In view of the problems experienced by the water sector as a whole and drinking water in particular, which relate to the quantities and quality of water flowing into the Iraqi territory from neighboring countries, which decreases annually or deteriorate qualitatively because of the implementation of neighboring countries for a large number of development projects without coordination with the Iraqi side. The Directorate General of Water in Iraq has taken some measures to address this issue through the installation of package water treatment units that contributed to reducing the water scarcity rate from 42% in 2006 to 20% in 2010 (Ministry of Municipalities and Public Works of the Iraq, 2010).

Surface water treatment is generally aimed at removing suspended materials that cause turbidity and color and odor change. Most of the methods used to treat this type of water have been limited to coagulation, flocculation, sedimentation, filtration and disinfection. The suspended material consists of organic and clay materials, and contains some microorganisms such as algae and bacteria. Due to the small size of these components and the large surface area compared to their weight, they remain stuck in the water and not deposited. Therefore, depending on their surface and chemical properties, and using flocculation processes, the main method of surface water treatment, where some chemicals are used to break the balance of the suspended materials and create conditions for deposition and removal in sedimentation basins. Sedimentation process is followed by filtration using sand filters to remove residual residues. The sedimentation and filtration processes are followed by the disinfection process prior to sending the water to the consumer.

After 2003, hundreds of regional development projects were completed to provide potable water to rural and remote areas in most governorates in Iraq. These projects consist of a package water treatment plant with a water network. As a result, the Contracts Department in Diwaniyah Governorate carried out several projects of the package water treatment plant (PWTP) units, where the number of them (more than 200) with capacity 14–400 $m^3 \cdot h^{-1}$ had been distributed throughout the districts of Diwaniyah governorate. For these projects is surface water. The source of potable water in the province of Diwaniyah is the river water, which comes from the Euphrates river. Therefore, all the units of drinking water purification is the water of the rivers for the purpose of treatment and making them drinkable. It is also known that the Euphrates river is considered to be turbid water, especially in the spring and summer seasons. As the collected water units use pressure filters to filter the water and remove turbidity. The high turbidity values of water cause great pressure on filters reducing their efficiencies, and this requires changing the filters materials, such as sand and gravel every month; therefore, the cost of operation and maintenance is increased and the number of operation hours is decreased, resulting in inefficiency of water purification units. Given that the turbidity values are very high from the surface water source of the Diwaniyah during most of the year, which makes coagulation and flocculation an important and decisive factor in removing the turbidity. The disinfection chlorine is less effective when the raw water is very high, that is, when there is a lot of particles in the water (particulate matter) because these particles are working to prevent the access of chlorine to the bacteria. Therefore, there is a need for inexpensive and sustainable prefabricated water parks that remove particles or decomposes from the supply of water supplies, and all components of these plants must operate efficiently. All the package water treatment plant contains mechanical flocculators, which suffers from continuous faults and needs periodic maintenance and needs electric energy to operate, which leads to an increase in the cost of water production and lack of quality of water produced. In this study, mechanical flocculation, which uses electric paddles will be replace with hydraulic flocculation, which uses gravity energy from water. This design uses a hydraulic process to reduce the complications associated with mechanical flocculation and to deal with the lack of electricity. The hydraulic flocculation has the advantage that the baffles achieve gentle agitation.

The process of flocculation is the aggregation of destabilizing particles in the microflocs and then in larger particles called flocs (Degrèimont, 1991). There are two types of flocculators: hydraulic flocculators, which stirring is achieved by baffling in horizontal flow or vertical flow baffles the flocculator channel, through a series of separate chambers

(Smet & Wijk, 2002) and mechanical flocculator which stirring is achieved by mechanical paddles, and impellers (Smet & Wijk 2002).

In developing countries, the hydraulic flocculator is preferred because of the ease of operation and maintenance, the absence of mechanical equipment, and the consumption of energy. The hydraulic flocculator does not require electricity but still uses the basic principles of flocculation. In this study, the water technology produced by AguaClara was adopted. Critical parameters affecting hydraulic flocculator design included water velocity, velocity gradient, retention time, water depth, and baffle geometry (Shultz & Okun, 1984; McConnachie, Folkard, Mtwali & Sutherland, 1999; Haarhoff & Van Der Walt, 2001). In the hydraulic flocculator the mixing is created by baffling in the channel that leads to abrupt directional changes in the flow (Bridgeman, Jefferson & Parson, 2009; Crittenden et al., 2012; Edzwald, 2013). Hydraulic flocculators are built on two fundamental ideas. The first is velocity gradient (G) [s^{-1}], and the second is $G\theta$, – a dimensionless measure of mixing. θ is the residence time of the tank, so G times θ yields a dimensionless number (Casey, Monroe & Lion, 2017; Marques & Ferreira Filho, 2017).

Computational Fluid Dynamics (CFD) package ANSYS Fluent 16.1 software, was utilized to help analyze the flow path in the flocculation of Al-Eskan package water treatment plant (EPWTP) in the south of Diwaniyah city in Iraq. This software is useful because it allows us to visualize the flow and understand how liquid behaves as it travels through the flocculator.

In this study, the type of flocculation basin will be change from mechanical to hydraulic. The current flocculation in the project is of mechanical type. The dimensions of the flocculator are width 2.5 m, length 4 m, and height 2.5 m. A major challenge in this project is the process of coordination between the amount of flow rate and the number, height and distances between the baffle in the flocculation. Another challenge to be addressed in this study is that the dimensions of the flocculator are constant and cannot be changed.

The design parameters of the hydraulic flocculation tank that were taken into consideration in this study are flocculator geometry, number and dimension of baffles, head losses, turbulent flow, water velocity, velocity gradient and hydraulic retention time.

The main objective of this study is to design a hydraulic flocculator basin instead of a mechanic for the EPWTP using a ANSYS Fluent CFD model, and to optimize the flocculation tank design. It is hoped that the hydraulic flocculator basin, which was designed in this study, will be construct in all the package water treatment plant in the Al-Eskan project to achieve values < 1 NTU.

Material and methods

Description of Al-Eskan package water treatment plant (EPWTP)

The package water treatment plant is a built-in tank system that combines all the necessary ingredients for coagulation, flocculation, sedimentation, filtration, and disinfection. This design makes it ideal for treating potable water and consumes less electrical energy and is quick to implement and can also be used to reduce suspended solids.

The rapid mixing tank is a 2,000-liter UPVC tank containing a rapid mechanical mixer for alum; then mixing alum with water and piping it into the mechanical flocculation. The flocculation basin consists of an electric mechanical mixer that moves the water and a slow motion to act as a collision and adhesion between the particles in the water and make it larger and then deposited in the sedimentation basin. The water is then transferred from the flocculation basin to the settling basin evenly from the bottom by pipes regularly distributed below the sedimentation basin. The sludge is periodically pulled out by an automatic valve. The treated water is collected through weirs and channels in the sediment basin surface for pumping to high pressure filters. The water coming from the settling basin enters the pressure filters to remove the remaining solid particles as the water passes through the layers of the different filtration materials and is constantly washed depending on the amount of turbidity entering. The water is then collected in a tank and the chlorine is added to the gas after mixing with the water for disinfection at the beginning and end of the project before pumping it to the consumers (Fig. 1).

The present study focused on studying the possibility of developing a 100 $m^3 \cdot h^{-1}$ package water treatment plant located in the Al-Eskan project in the south of Diwaniyah city, in Diwaniyah governorate (Iraq). The project of EPWTP is 10 units of water collected each unit of capacity of 100 $m^3 \cdot h^{-1}$ and each unit working in parallel pool water

FIGURE 1. Al-Eskan package water treatment plants

in one storage basin dimensions of 12 × × 2.2 × 2.2 m with a collection basin and pressure filters and the pressure pipe 10 inch and 2 pumps 75-hp. The EPWTP is equipped with raw surface water from the Diwaniyah river, which is one of the Euphrates river by pumps 100 m away from the station. The population served by this project is about 100,000 people (Figs. 2 and 3).

Figure 3 show the EPWTP description of technical and technological parameters for the operation of separate unit processes of water treatment.

The dimensions of the EPWTP at a capacity of 100 $m^3 \cdot h^{-1}$ are 12 × 2.20 × × 2.20 m (length × width × height). Alu-

FIGURE 2. Mechanical flocculator in EPWTP

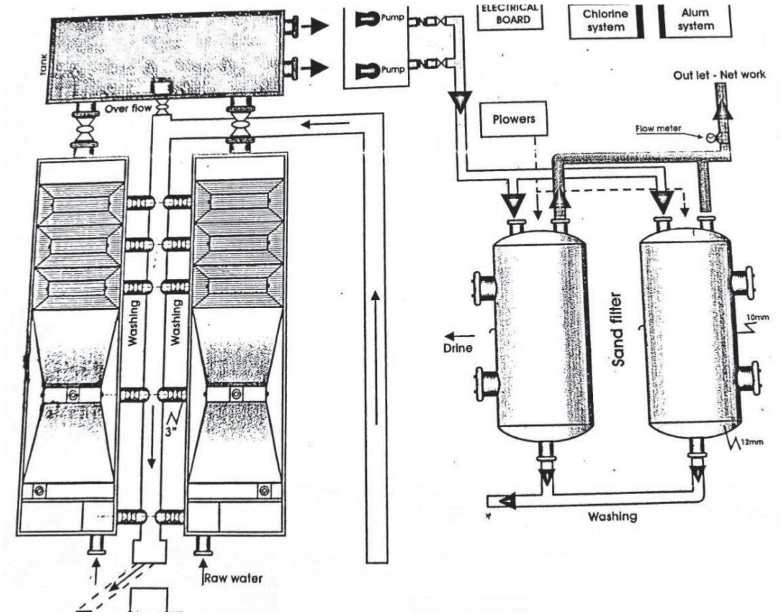

FIGURE 3. A technological scheme for purifying the water

minum sulphate is used as a coagulant, which is added in 5 kg to the external rapid mixing basin with a capacity of 2,000 L (2.5 $g \cdot L^{-1}$) in the winter seasons. The turbidity values are 30 NTU and 10 kg in summer seasons (5 $g \cdot L^{-1}$) when turbidity reaches 200 NTU. Furthermore, in disinfection process, liquid chlorine is added at a rate of 10 $mg \cdot L^{-1}$. Below is a description of the practical aspect:

1. Laboratory experiments and laboratory tests were carried out on one--year EPWTP from January 2016 to December 2016. The limits of inlet turbidity were 20–200 NTU.
2. The computational fluid dynamics model was used to design a vertical hydraulic flocculater basin using the ANSYS Fluent 16.1 program.
3. Several geometric parameters have been tested related to the design of the flocculater basin, through which the optimum design can be determined for flocculation.
4. The jar test was performed using the Lovibond device to determine the optimum value of the aluminum sulphate concentration.
5. The samples were collected to measure the turbidity from the intake of EPWTP, the entrance to the EPWTPs, the flocculation basin, the sedimentation basin, the water filters and the storage and assembly basin. Total suspended and turbidity levels using the HACH2100 turbidity meter and all tests were carried out in the EPWTP laboratories. The highest value of the turbidity is 200 NTU, so this value was adopted for the turbidity in the experiments of this study (Fig. 4).

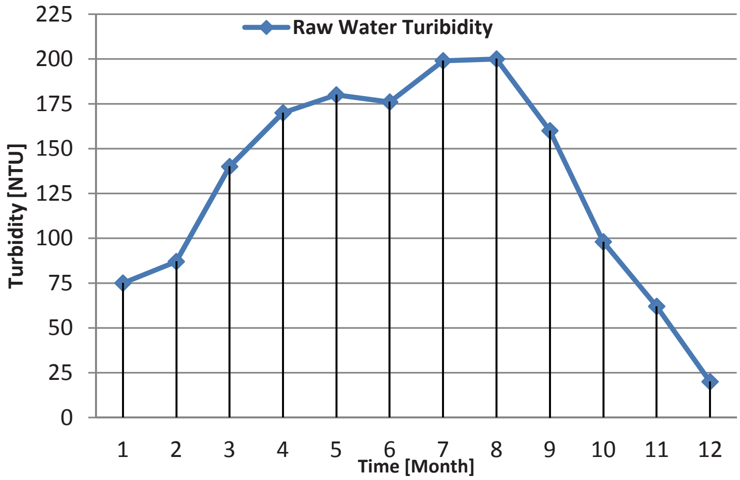

FIGURE 4. Raw water turbidity values for the period from January 2016 to December 2016

Flocculation design criteria

Typical design criteria for hydraulic flocculation are shown in Table 1. The hydraulic guide design criteria are: velocity gradient, detention time, channel velocity. Velocity gradient × velocity gradient refers to the level of turbulence. The velocity gradient × detention time is associated with a number of particle collisions.

CFD model and analysis

Vertical hydraulic flocculator geometry

A schematic diagram of a typical vertical hydraulic flocculator is shown in Figure 5. The design variables that have been taken into account when designing the flocculate basin include the flow rate (Q) [$m^3 \cdot h^{-1}$], the number of baffle per

TABLE 1. Flocculator design criteria

Designation	Unit	Range
Velocity gradient	s^{-1}	10–100, typical 45–90 (Smet & Wijk, 2002) 20–100 (Schulz & Okun, 1984) 100 (Degreìmont, 1991)
Velocity gradient × detention time	–	30 000–150 000 (Smet & Wijk, 2002) 20 000–150 000 (Schulz & Okun, 1984)
Detention time	min	15–20 (Smet & Wijk, 2002) 10–15 (US Environmental Protection Agency, 1998)
Channel velocity	$m \cdot s^{-1}$	0.1–0.3 (Smet & Wijk, 2002) 0.1–0.3 (Schulz & Okun, 1984)

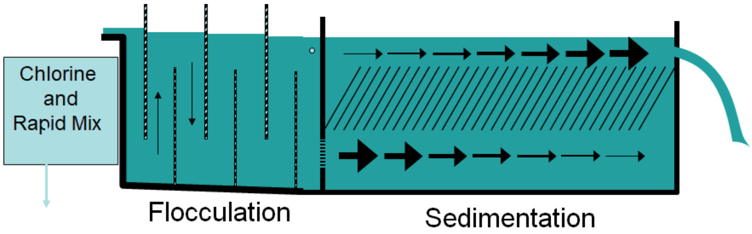

FIGURE 5. Vertical hydraulic flocculator geometry

section [N], the baffle spacing (*BS*) [m], the baffle dimensions, head losses [m], basin depth (*FH*) [m], clearance height (*CH*) [m], and water depth (*L*) [m]. We have been exploring by using the ANSYS Fluent program different ratio of *FH*/*BS* and *CH*/*BS*.

Using the results of the analysis of these ratios we obtain the ideal design of the flocculator basin. The energy dissipation rate indicates that the breakup of flocs is the most important constraint. The more uniform energy dissipation rate means the optimum flocculator design.

Procedures for tank design and configuration

The flocculation basin available dimensions are 4.0 × 2.2 × 2.2 m (length × × width × height) with a wall thickness of about 0.8 cm in EPWTP. From the design criteria imposed by the reality of the project, the depth of the flocculator basin is the depth of the sedimentation basin. The water level at the end of the flocculator basin is similar to that of the water level in the sedimentation basin. The width of the channels is determined by the need to construct the channel using humans. The channel width is also determined by the efficiency of the flocculator basin which was 0.70 m. The distance between the baffles and their number is determined by the flow rate. The height of the vertical hydraulic flocculatore is determined by the height of the sedimentation basin, which is 2.0 m. As package water treatment plant need longer residence time and more baffles number. The width of the flocculator basin is determined by the width of the settling basin, which is 2.2 m. The hydraulic vertical flocculator in EPWTP is divided into three sections filled with vertical baffles (Fig. 6). The purpose of adding baffles is to increase gradient velocity (*G*) by acting as an obstacle and forcing water through a restricted flow path. A hydraulic flocculator design was created based on optimized parameters available in the previous studies (McConnachie & Liu, 2000; Haarhoff & Van Der Walt, 2001). The initial design divided the total minimum mixing value (60,000) evenly among the three sections, with each section having an even velocity gradient of 50 s^{-1}. The current setup has a baffle spacing of 10 cm with 22 baffles per section. ANSYS Fluent CFD software will be used to find the best design for the vertical hydraulic flocculator to get the efficient of turbidity removal < 1 NTU.

Velocity gradients

As previous studies have shown, velocity gradient is the central variable to improve flocculation performance. The velocity gradient value is usually ex-

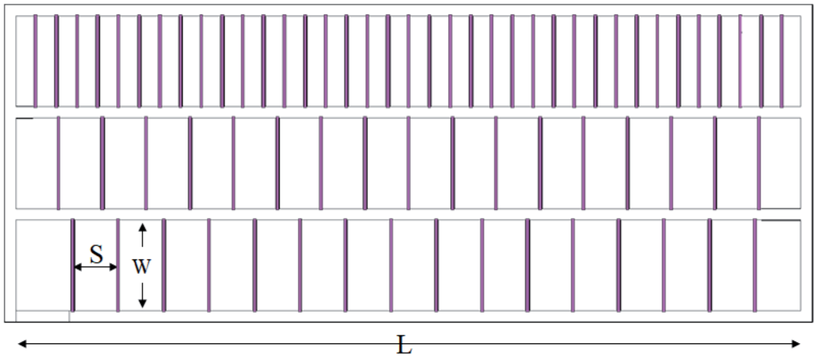

FIGURE 6. Vertical hydraulic flocculator layout (top view)

pressed as a function of total energy input for each total flocculator volume (Eq. 1). It can also be expressed in terms of total head loss and retention time (Eq. 2). The expression of head loss is given by Equation 3. The physical interpretation of the velocity gradient value is, however, not a velocity gradient, but rather an energy dissipation rate per unit volume. The formulation used in this study to express G, is given by Equations 2 and 4 (Lawler & Nason, 2004):

$$G = \sqrt{\frac{P}{\mu}} \tag{1}$$

$$G = \sqrt{\frac{\rho g h_1}{\mu \theta}} \tag{2}$$

$$G = \sqrt{\rho \frac{\varepsilon}{\mu}} \tag{3}$$

$$h_1 = \left[\sum K_{\text{minor}} + \frac{n \cdot f \cdot L_s \cdot (w+b)}{2 \cdot w \cdot b} \right] \cdot \frac{V^2}{2 \cdot \mathrm{g}} \tag{4}$$

where:

P – total power input to flocculator [N·m^{-1}·s^{-1}],

V – average channel velocity [m·s^{-1}],

h_1 – head loss across flocculator [m],

K – empirical head loss coefficient for a 180° bend in a square channel,

n – number of 180° turns in flocculator,

μ – molecular viscosity [Pa·s],

w – channel width [m],

L_s – baffle length [m],

b – baffle space [m],

f – friction factor,

g – gravity 9.81 m·s^{-2},

θ – retention time [s].

CFD model

In order to better understand the behavior of the fluid in the flocculation tank, the CFD simulation has modeled the tank using ANSYS Fluent 16.1 software. This approach allows the analysis of different geometries, flows and boundary conditions without the difficulty of setting. The results produced by the simulation enables examining detailed profiles of velocity, turbulence energy dissipation, turbulent kinetic energy, and any derived parameter in terms of these variables. The turbulent flow in the flocculator was simulated with the Navier–Stokes equations and the standard k–ε model. The vertical baffles were spaced using equations written in ANSYS Fluent 16.1 software (by use user defend function UDF) created to test for different velocity gradients: G and amount of mixing – $G\theta$. The velocity gradient value for each cell of the computational grid was calculated using Equations 2 and 4 and simulate in software by UDF. The clear water density and viscosity were used while the dissipation rate (ε) was obtained from solving the k–ε turbulence model. The top part of the flocculation is open, so a symmetry boundary conditions is employed. The inlet boundary conditions are inlet velocity 0.5 $m \cdot s^{-1}$, with turbulent intensity and hydraulic diameter 10% and 0.25 m respectively, and the outlet is set to pressure outlet 0 Pa. Pressure outlet applies with second order upwind settings for momentum, turbulent kinetic energy and dissipation rate. Full-scale hydraulic vertical flocculators at the EPWTP were simulated. In order to reduce the number of computational cells only the first five channels were modeled (Fig. 7).

Results and discussion

To find the optimal design of the vertical hydraulic flocculator, the energy dissipation rate must be uniform at the different ratios of the tank height to the distance between baffle (FH/BS), and at the different ratios of clearance height to the distance between baffle (CH/BS). Since the energy dissipation rate is the basic parameter affecting the particle collision, it is reasonable to assume that the uniform profile of the energy dissipation rate will give the best performance of the vertical hydraulic flocculator.

Figures 8 and 9 shows that the results are not sensitive to the change in clearance height. The contours of the turbulent dissipation rate were compared to clearance heights by 1BS m and 1.5BS m. These results show that the active turbulent dissipation rate zone is the same for both reactors, about twice the length of the baffle spacing. From Figures 8 and 9 we concluded that high clearance must be no smaller than baffle spacing.

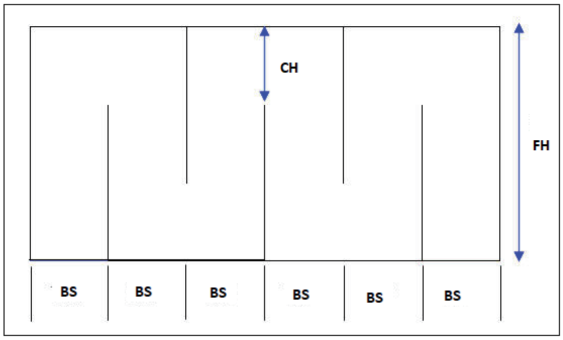

FIGURE 7. Vertical hydraulic flocculator tank geometry

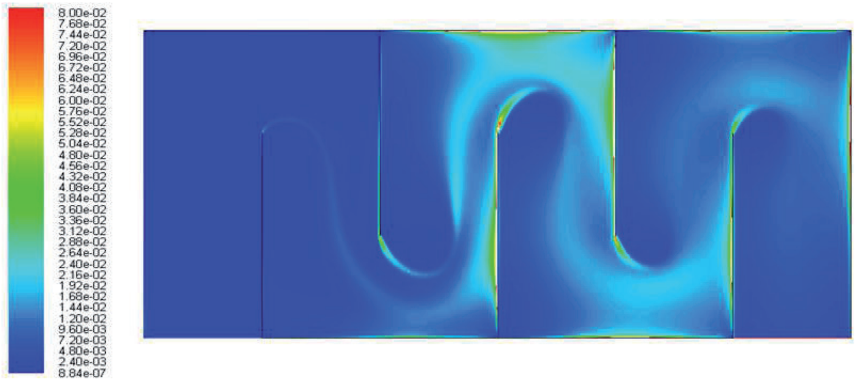

FIGURE 8. The contours of the turbulent dissipation rate for clearance heights with 1*BS*

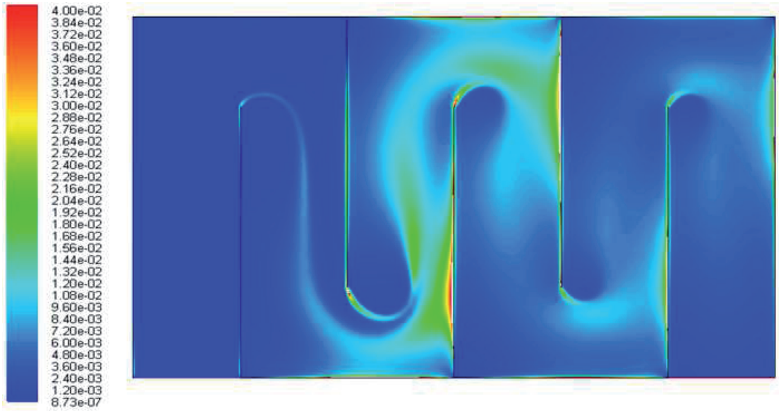

FIGURE 9. The contours of the turbulent dissipation rate for clearance heights with 1.5*BS*

We would also like to begin our investigation into geometric space by having more interference in the energy dissipation zone. Using these two impediments, we come up with the initial $FH/BS = 7.5$. We believe that the rate of energy dissipation is fairly uniform. Since this is our starting geometry, there is no other geometry to compare with. So this will be the new incumbent (Fig. 10).

From the initial dimensions of the flocculator in Figure 10, we see that there is a large blue zone at the inner bend. By minimizing the spacing of the fenders, we hope to reduce the inert area. Therefore, in Figure 11, we increase the ratios of $FH/BS = 11.25$, but we did not notice any significant change in the turbulent dissipation rate. This is consistent with the findings of most researchers (Casey et al., 2017; Marques & Ferreira Filho, 2017).

In Figure 12a, the ratio change was tested, where it was observed that the ratio of FH/BS of 15, which provides overlapping zone. Reducing the interference of the tail of the energy dissipation zone may lead to a more uniform distri-

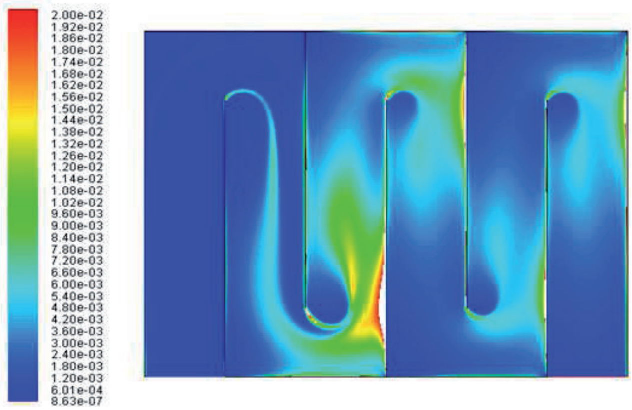

FIGURE 10. The contours of the rate of energy dissipation at *FH*/*BS* = 7.5

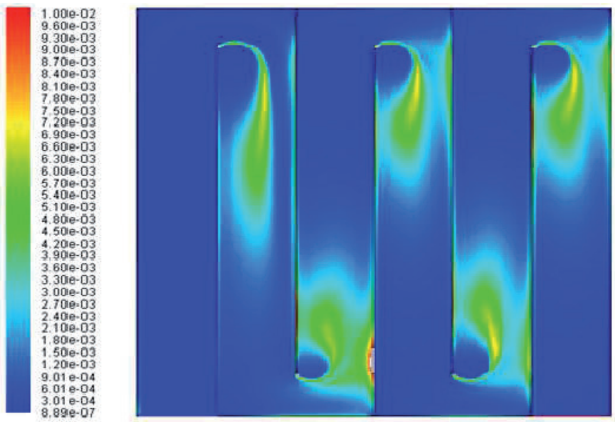

FIGURE 11. The contours of the rate of energy dissipation at *FH*/*BS* = 11.25

bution. In the Figure 12b, the ratio was increased to 22.5, where it was observed that these dimensions of the basin give us this geometry rate of energy dissipation more uniform than the previous rate. This geometry configuration will be the new incumbent. Since changing this geometric space gives the desired result. Results represented and analyzed using CFD software included plots of water contours of strain rate and contours of turbulence dissipation rate.

The value of $G\theta$ decreases with the increase in the height of the flocculation tank, indicating that the most efficient flocculation occurs in the *FH*/*BS* ratio of 22.5. Among the results is that the hydraulic retention time of the water in the flocculator is 20–25 min. The optimal design was to use a single long flocculator by dividing it into three channels. The results showed that the best velocity gradient of water mixing in the flocculation tank is 40 s^{-1}. The vertical

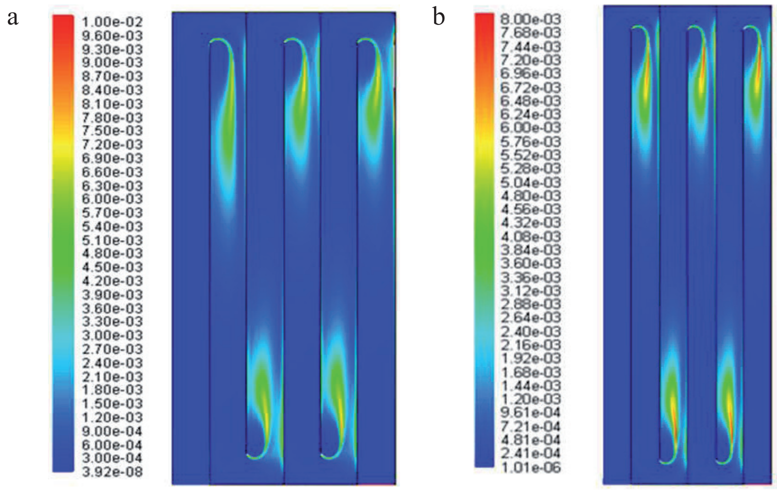

FIGURE 12. The contours of the rate of energy dissipation at $FH/BS = 15$ (a) and $FH/BS = 22.5$ (b)

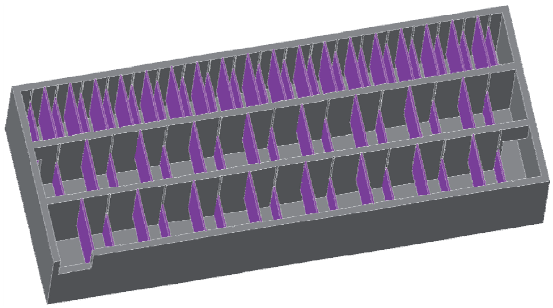

FIGURE 13. Three section arrangement of top and bottom baffles in vertical hydraulic flocculation

tank to be constructed consists of three channels, each 0.70 m wide and 4.0 m long, with baffles spacing of 10, 15, and 20 cm. There are 80 baffles and the tank has a retention time of 20 min, and the velocity varies from 0.2 $m \cdot s^{-1}$ in the first row to 0.06 $m \cdot s^{-1}$ in the third row. The velocity gradient varies from 60 s^{-1} in the first row to 10 s^{-1} in the third row (Fig. 13). The results above correspond to the results of previous studies such as Schulz and Okun (1984), McConnachie and Liu (2000), Haarhoff and Van Der Walt (2001), Lawler and Nason (2004), Casey et al. (2017), Marques and Filho (2017).

Conclusions

Our aim was to experimentally define G and $G\theta$ to design vertical hydraulic flocculation basin and to improve the effluent turbidity removal. Computational Fluid Dynamics (CFD) package, ANSYS Fluent 16.1 software have been used to hydraulic flocculators for Al-Eskan package water treatment plant

(EPWTP). The design approaches can be utilize to find the optimal geometry for flocculation tank. The results of the study indicate that the design of the vertical hydraulic flocculation optimization in terms of uniformity occurs when the flocculation tank height to baffle spacing ratio of 22.5, and the clearance height to baffle spacing ratio of 1. Overall, the design of the flocculation tank produced reasonable results that matched the expected results of the hydraulic flocculation tanks contained in the previous studies.

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Summary

Optimal design parameters for hydraulic vertical flocculation in the package surface water treatment plant. After 2003, hundreds projects were completed to provide drinking water to rural areas in most governorates in Iraq. These projects consist of the package water treatment plant, which treats surface water from the Tigris and Euphrates rivers. All the package water treatment plant contains a mechanical flocculators, which suffers from continuous faults and needs periodic maintenance and needs electric energy to operate, which leads to an increase in the cost of water production and lack of quality of water produced. In this project, the possibility of changing the type of flocculators from mechanic to hydraulic was tested for a 100 $m^3 \cdot h^{-1}$ package water treatment plant in the Al-Eskan water treatment project in the south of Diwaniyah city in Iraq. There are many challenges facing the design involving findings ways to improve the efficiency of the flocculation system. Computational Fluid Dynamics (CFD) package, ANSYS Fluent 16.1 software have been used to simulate turbulent fluid flow in hydraulic flocculators for Al-Eskan package water treatmen plants (EPWTP). The flocculator simulations in ANSYS Fluent are used to obtain turbulent kinetic energy dissipation rate to determine the distance between baffles, the quantity of baffles, velocity gradient, residence time, and flocculation performance. The results obtained from ANSYS Fluent simulation are used in designing a hydraulic flocculator, so our finding can be utilized to validate the hydraulic flocculator model. The results confirmed that the method used to design certain parameters of the tank are fairly accurate. Overall the design of the flocculation tank produced reasonable results which match expected results of hydraulic flocculation tanks found in literature. The results of the report suggest that a height to baffle spacing ratio of 22.5 creates intersecting energy dissipation regions that produce the greatest formation of flocs per reactor volume.

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