# Baffles Shape and Configuration Effect on Performance of Baffled Flocculator

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**Abstract- Flocculation process is used to agglomerate colloids to form large and heavy flocs. It is accomplished using mechanical or hydraulic slow mixing. The hydraulic mixing is usually achieved using baffles. The aim of this study is to conduct experimental work to study the effect of baffles shape and configuration on baffled flocculator performance. The work includes 304 experiments conducted in a pilot plant of baffled flocculator. Two arrangements of three baffle shapes (blind baffles, baffles of rectangular slot and baffles of circular slots) were adopted. During each experiment, water turbidity and temperature, influent flow rate and head loss were measured. The main outcomes of this study are; (1) for all baffle types and arrangements, flocculation efficiency (FE) increases with the increase of velocity gradient (G) till it reaches a maximum value, then, it decreases and the G value which produces the maximum FE varies with detention time (t), (2) within the applied range of Gt values (10231-25304), the correlation between FE and Gt is weak to moderate positive and varied according to baffles type and arrangement, (3) within the applied range of initial water turbidity (IWT) values (18.1-196) NTU, the correlation between FE and IWT is weak positive to good positive represented by logarithmic relationship, and (4) within the implemented baffle types, the blind baffles type gives the highest FE values for all the baffles number as compared with the other baffle types. Also, the most frequent head loss coefficient values were obtained.**

**Keywords —Water treatment; baffled flocculator; performance; baffles shape; configuration.**

## I. Introduction

Water in nature, whether it is surface or ground water, includes many suspended and dissolved impurities [1]. Most of suspended water impurities are colloids (in the microscopic size range [2] or have a size less than 1μm [3]). Colloids impurities have negative charge and, thus, they repel from each other and retain in dispersed state, i.e., they are non-settable suspended solids. The presence of suspended solids in water increases the water turbidity and, hence, gives the water bad taste, color and odor. Thus, the raw water withdrawn from the different water sources is treated before use to remove these impurities and make the water chemically and microbiologically safe and palatable to drink. Sedimentation and filtration processes are used for removing the suspended solids by settling under gravity and by passing the water through a porous media, respectively. Coagulation followed by flocculation processes are usually used as preparatory step for enhancing the performance of sedimentation and filtration processes [4]. Coagulation is the process of colloids destabilization by the addition of positive ions (coagulants) [3]. Flocculation process is agglomeration of destabilized particles by allowing the colloids to approach to each other and build into larger and heavier settable or filterable flocs [5].

Flocculators are classified into two main types; mechanical and hydraulic flocculators. In hydraulic flocculators, the energy of flowing water is used to produce the power dissipation required for mixing [6]. That can be achieved through the use of baffles or coiled tube. In baffled flocculators, mixing is usually produced from the turbulence caused by the change in flow direction (180° turns) at the baffles end [7]. Baffles are of two types; around-the-ends and over-and-under baffles [5]. Hydraulic flocculators are characterized by their simplicity and effectiveness, low maintenance cost, no operating staff, zero operating cost and the ability to produce very large flocs. However, they have little flexibility [3].

Many previous studies were conducted on baffled flocculator. Bhargava and Ojha [8] evolved the design of baffled flocculators by introducing a methodology based on nomographs. McConnachie [9] and McConnachie and Liu [10] conducted experimental studies to assess the performance of around-the-end type baffled flocculator. Swamee [11] introduced optimum design for around the end type baffled flocculators by formulating a geometric programming problem with zero degree of difficulty. Haarhoff [12] developed a two-step design procedure for around-the-end baffled flocculators to overcome the problem of inflexibility and cope with the variations in water quality and flow rate. Haarhoof and Van der Walt [13] used computational fluid dynamics (CFD) modeling technique to investigate the performance of around-the-end baffled flocculator. Liu et al. [14] developed a method used in conjunction with CFD technique for designing around-the-end baffled flocculator. Bridgeman et al. [15] used CFD technique to simulate a full scale over-and-under type baffled flocculator. Weber-Shirk and Lion [16] developed a mathematical model to characterize flocculation process in hydraulic flocculators. Vadasarukkai and Gagnon [17] evaluated the mixing condition in over-and-under type baffled flocculator applying CFD modeling technique. Finally, Joodi [18] simulated the turbulence flow in over-and-under baffled flocculator using a 2D finite element model.

All the aforementioned studies did not consider the effect of baffles shape and arrangement on performance of baffled flocculator which is the motivation of the present study. Thus, the aim of this study is to conduct experimental work to study the effect of baffles shape and configuration on performance of baffled flocculator (efficiency and head loss coefficient). In this study, the performance of baffled flocculator was measured using a 30 minutes settling test.

## II. Materials And Methods

### A. Design parameters

The main parameters affecting the degree of flocculation are detention time and velocity gradients [2]. Herein, detention time is the duration of water retention in flocculation unit and it is considered as a significant parameter for this unit since a sufficient detention time can increase the opportunity of large flocs generation and subsequently increase the efficiency of solid removal in sedimentation unit. The detention time is defined as [19];

(1)

where;

t= detention time, min.
V= water volume in flocculation tank, $m^3$.
Q= influent flow rate, $m^3$/min.

The production of a turbulent motion in a suspension is the only way to promote the contact between suspended solid particles. This can be done by inducing velocity gradients through agitation. More particle contacts occur as the velocity gradients increased. However, the increase of velocity gradient increases the shear stress which causes the breakdown of the large flocs. Thus flocculation process needs an adequate velocity gradient to increase the chance of particles contact and keep the flocs in suspension but prevent the flocs breakdown [19]. For that reason, velocity gradient is an essential parameter for designing the flocculation units.

Velocity gradient (G) in flocculation process is influenced by the energy supplied and the dissipation rate of energy [20]. It is obtained as [2], [5], [6], [8], [10], [11], [12], [13], [19], [20], [21], [22], [23], [24], [25];

$$\sqrt{P} \qquad (2)$$

where;

G= velocity gradient, $sec^{-1}$.
P=input water power, N.m $s^{-1}$.
μ = dynamic viscosity of water, N.s/$m^2$.
V = water volume in flocculation tank, $m^3$.

In baffled flocculator, the input power to water is the dissipated power caused by baffles and can be obtained as [6], [8], [19];

(3)

where;

ρ = mass density of water, kg/$m^3$.
g= acceleration due to gravity, m $s^{-2}$.
Q= water flow rate, $m^3$/s.
P= input water power, N. m $s^{-1}$
$h_l$= head loss due to baffles, m.

For flocculation tank has a uniform cross sectional area, the head loss can be defined as water level difference between inlet (tank beginning) and outlet (tank end) [26]. The head losses in baffled flocculator are due to channel friction and 180° sharp bends at over-and-under or around-the-end baffles [8]. The channel friction head loss is usually neglected [8, 12] and, thus, the head loss in baffled flocculator is mainly due to the 180° sharp bends and can be calculated as [8], [12];

$$— \qquad (4)$$

where:

$h_l$ = total head loss in baffled flocculator, m.
NB= number of baffles.
K= head loss coefficient.
v= flow velocity through the baffle slot, m $s^{-1}$.
g=acceleration due to gravity, m $s^{-2}$.

McConnachie and Liu [10] showed that the head loss coefficient (k) equals 3.2 when the baffles slot width equals the channel width and k equals 6 for other types of grid baffles. Bhargava and Ojha [8] showed that best agreement of experimental and theoretical head loss values is obtained at k equals 1.5 and Swamee [11] specified k value equals to 2.

For baffles provided with circular orifices, the head loss through the orifice can be determined using the equation proposed by Renolds and Richards [cited in 19];

$$A\sqrt{2} \qquad (5)$$

where;

Q= flowrate through orifice, $m^3$/sec.
$C_d$= coefficient of discharge= 0.6 to 0.8 [19].
A= orifice area, $m^2$.
h= head loss through the orifice, m.

Flocculation process performance is also dependent on a dimensionless number Gt (product of G and t) which is called Camp number [27]. For baffled flocculators, the values of t, G and Gt recommended in the previous studies are shown in Table I.

TABLE I
Design Parameters of Baffled Flocculators

| Parameter | Value | Ref. No. |
|---|---|---|
| t (min) | 16.7 | [8] |
| | 15-20 | [10] |
| | 10-20 | [Cited in 9] |
| | 20-25 | [9] |
| G ($sec^{-1}$) | 30-60 | [8] |
| | 10-100 | [10] |
| | 20-74 | [11] |
| Gt | $10^4$-$10^5$ | [8], [10], [11] |

### B. Experimental Work

1) *Pilot Plant of Baffled Flocculator:* Flocculation experiments were conducted in a pilot plant manufactured for this study. The plant is composed of; (1) flocculation tank provided with baffles, (2) feed and rapid mix tank, (3) electric water pump, (4) flow meter and (5) pipes and valves. Flocculation tank is rectangular of 2.4m length, 0.3m width and 0.8m total depth. It is provided with 23 rectangular baffle frames. The tank walls and bottom are made of 10 mm thick reinforced glass. It is placed on white cork board underlined by plywood base and bounded by steel protection frame. The influent pipe discharges into the tank head and the water leaves the tank through an outlet pipe fixed at a height of 0.6m above the bottom of tank end. At the tank bottom, a drain pipe was fixed for emptying the tank after each experiment. The feed and rapid mix tank is a plastic tank of 500 liter capacity. It is used to feed the influent water to the flocculation tank and perform the coagulation process via rapid mixing. The rapid mixing was achieved using recirculating pump which draws/recirculates the water from/to the feed tank. The tank is provided with two openings; one near the tank bottom and the other near the tank top. The lower opening is connected to the influent and recirculating flows pump which recirculates the water through a pipe connected to the top opening and, also, discharges the influent water to the flocculation tank after passing it through the flow meter. The influent flow rate is controlled using a flow meter with a readings range of (10-130) l/min. The flocculation and feed and rapid mix tanks are emptied after each experiment using a submersible pump. Fig.1 shows a schematic diagram of the pilot plant. All the baffles are made of 6mm thick glass. To study the effect of baffles shape on performance of baffled flocculator, three baffle shapes were used; (1) blind baffles, (2) baffles have rectangular slots and (3) baffles have circular slots. The total number of blind baffles is 23; 12 Nos. of 0.8m height and 0.3m width and 11 Nos. of 0.6m height and 0.3m width. The baffles with rectangular slots have slot dimensions of (2×15) cm, (4×15) cm or (6×15) cm. 11 Nos. of these baffles have a slot in the top edge and 12 Nos. of these baffles have a slot in the bottom edge. The baffles have circular slots; each has 6 circular slots of 2.5 cm diameter. Fig.2 shows photos of the baffles provided with rectangular and circular slots. The baffles were placed into two arrangements. In arrangement No.1; the baffles were placed at equally spacing of 10cm c/c. In this arrangement, the experiments were conducted using 5, 10, 15, 20 and 23 baffles as shown in Fig.3. In arrangement No.2, the experiments were conducted using 5, 10, 15 and 20 baffles. Herein, the baffles were distributed adopting the spacing shown in Fig.4.

2) *Preparation of Synthetic Turbid Water:* In this study, all the experiments were conducted using synthetic turbid water (STW). STW was prepared by adopting the procedure followed in the previous studies [28], [29], [30] in which the steps are:

1. Prepare a concentrated stock suspension of kaolin by adding of 10g kaolin powder to 1 liter of tap water.
2. Agitate the suspension using electrical mixer for 60min to get a homogeneous mix.
3. Left the suspension for 24 hrs. to insure kaolin complete hydration.

According to Šćiban et al. [30], the addition of 2.5ml, 5ml or 10ml kaolin stock suspension of 10g/l concentration to 1 liter of tap water will result STW has a turbidity of 17.5, 35 or 70 NTU, respectively. In this study, the tap water was drawn from the water network of Basra city and it was found (based on turbidity measurements) that this water has variable turbidity.

In this study, 500 liter of STW was prepared for each individual experiment. 500 liter of STW has turbidity value of approximately equals to 17.5, 35, 70 and 105 NTU was prepared by adding 1.25, 2.5, 5 or 7.5 liter of kaolin stock suspension to 500 liter of tap water, respectively. These stock suspensions were prepared by adding 12.5, 25, 50 and 75 g to 1.25, 2.5, 5 and 7.5 liter of tap water, respectively. The apparatuses used in preparing the STW include; analytical balance, electrical mixer and turbidity meter.

*3) Determination of Optimum Alum Dose:* The performance of flocculation process is influenced by the efficiency of coagulation process and mainly on the applied coagulant dose. In order to eliminate the impact of coagulation process on performance of baffled flocculator, all the flocculation experiments were conducted using optimum coagulant dosages. In this study, aluminum sulfate or alum ($Al_2(SO_4)_3.18H_2O$) was used as coagulant. The optimum alum dosage is dependent on turbidity of raw water and can be found using jar test [19]. Thus, four optimum alum dosages were obtained for the four STWs. The optimum alum dosages were obtained using Jar test device composed of four paddle stirrers in four jars. Table II shows the results of jar test including the values of optimum alum dosages for each of the four STW concentrations. These alum dosages were applied in carrying out the flocculation experiments.

*4) Procedure of Flocculation Experiments:* 304 flocculation experiments were performed using the pilot plant of baffled flocculator in accordance to the following procedure:

1. Preparing the stock suspension of kaolin.
2. Providing the pilot plant of baffled flocculator with specific baffles type, number and arrangement.
3. Filling the feed and rapid mix tank with tap water.
4. Addition of kaolin suspension to the feed and rapid mix tank to produce the STW.
5. Closing of V2 valve and opening of V1 valve, see Fig.1.
6. Turning on the pump to recycle the water and achieve the mix of kaolin suspension with tap water for 5min.
7. Turning off the electrical pump.
8. Addition of the suitable optimum alum dosage to feed and rapid mix tank and turning on the pump to mix the tank contents for duration of 1min. and achieve the coagulation process.

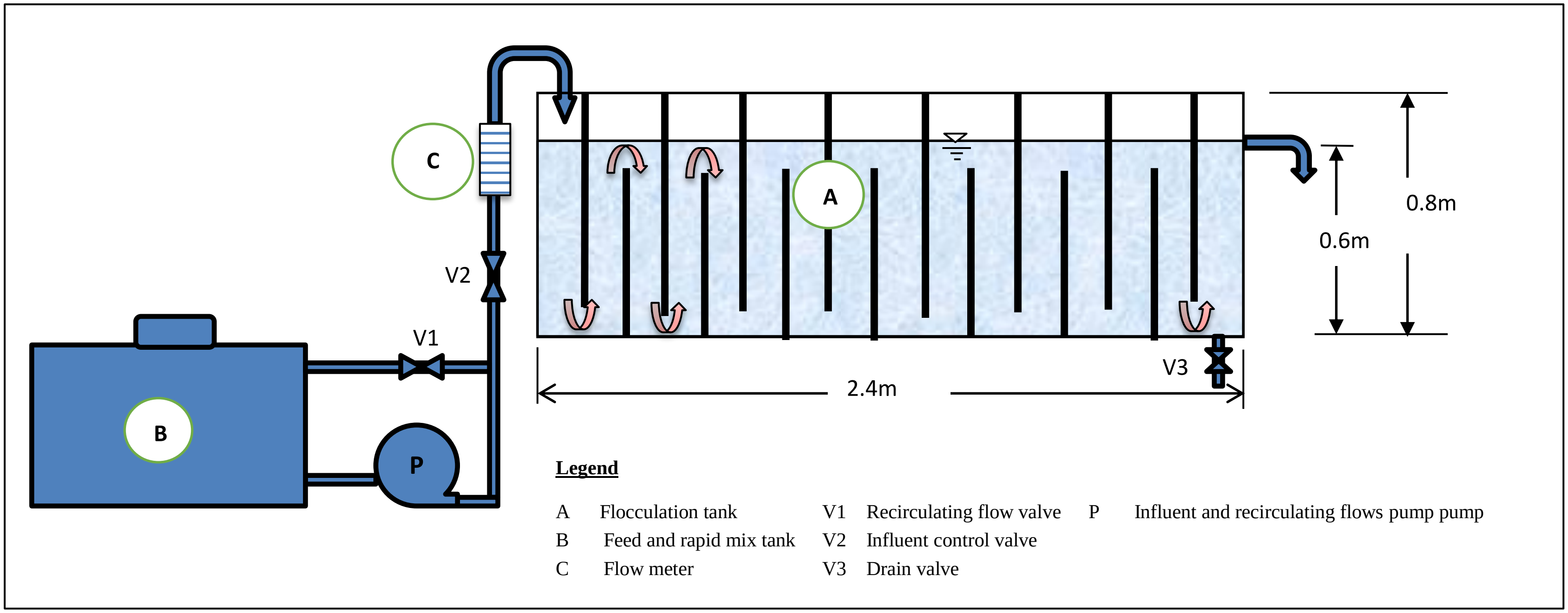



Fig.1 Schematic diagram of flocculation pilot plant

| | | | | |
|---|---|---|---|---|
|  |  |  |  |  |
| Baffle with rectangular slot of (2×15)cm. | Baffle with rectangular slot of (4×15)cm | Baffle with rectangular slot of (6×15)cm | Baffle with circular slots | |

Fig. 2 Baffles shape

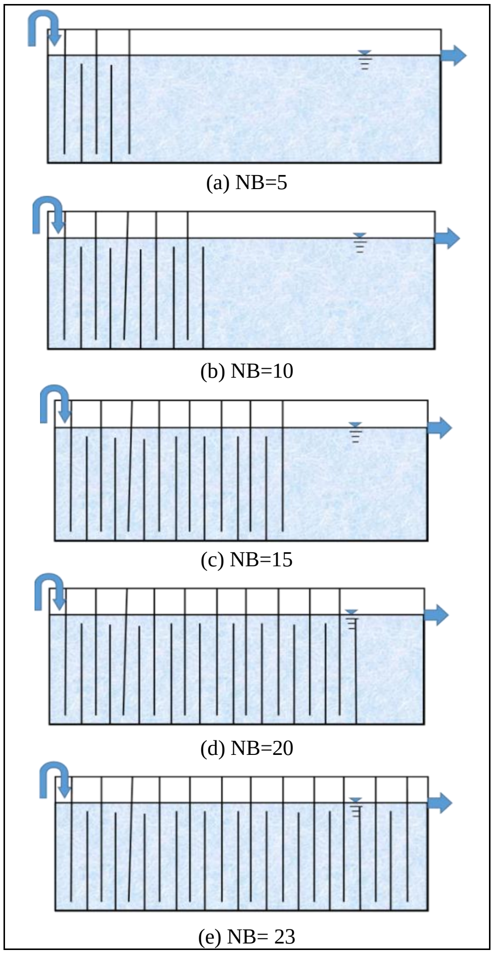



Fig.3. Baffles arrangement No.1

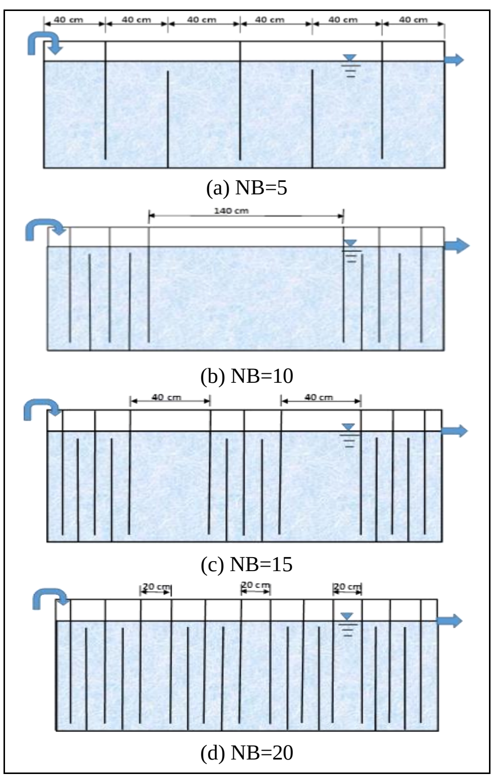
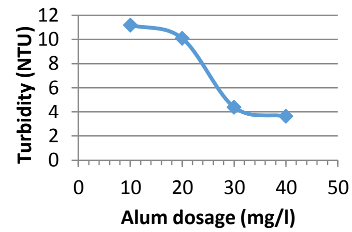
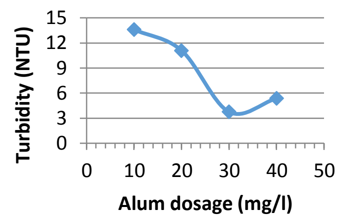
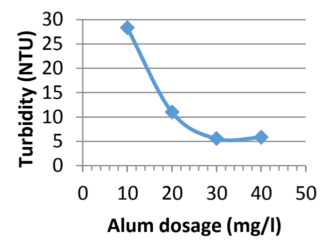
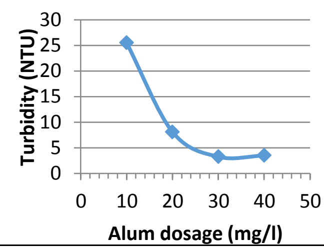



Fig.4 Baffles arrangement No.2

TABLE II
JAR TEST RESULTS

| STW conc. (mg/l) | Residual turbidity verses alum dosage | Optimum alum dosage (mg/l) |
|---|---|---|
| 25 |  | 40 |
| 50 |  | 32 |
| 100 |  | 32 |
| 150 |  | 32 |

9. Turning off the pump.
10. Closing of V1 valve and opening of V2 valve.
11. Turning on the pump and specifying the desired influent flow rate by controlling valve V2 with observing the reading of flow meter.
12. Recording of water temperature using thermometer (model KT300). The specification of water temperature is necessary to determine μ in Eq. 2.
13. Collection of water sample from the effluent and measure its turbidity.
14. Measuring the water depths at tank beginning and end to determine the head loss.
15. Conducting 30 min. settling test for the effluent water sample and, then, measuring the residual turbidity.
16. Emptying, cleaning and drying the flocculation tank. The tank is emptied by opening V3 valve and with the aid of submersible pump.
17. Emptying and cleaning the feed and rapid mix tank.

### *C. Efficiency of Baffled Flocculator*

The efficiency of baffled flocculator has been assessed using the percentage of turbidity removal during a 30 minutes settling test. The percentage of turbidity removal is defined using Eq.6. It was calculated for each experiment using the measured values of initial and final (after 30 min. settling) turbidity.

$$\frac{\quad}{\quad} \qquad (6)$$

where; FE is flocculation efficiency (%), IWT and FWT are initial and final water turbidity values (NTU), respectively.

## III. Results and Discussion

In this study, the experimental work includes 304 flocculation experiments conducted to study the effect of baffles shape and configuration on performance of baffled flocculator. The performance was studied considering the design parameters; t, G and Camp number (Gt). t was calculated using Eq.1 with adoption of measured influent flow rate during each experiment and the volume of water in the flocculation tank. The influent flow rates were controlled using the flow meter to be 17.3, 21.6, 28.8 or 43.2 l/min. G was determined using Eq.2 in which the input water power was calculated using Eq.3 with the adoption of measured total head loss value in each experiment and the value of dynamic viscosity (μ) relating to each measured water temperature was obtained from a table relating μ to water temperature and cited in [31]. Camp number was determined by multiplying t and G values.

The minimum and maximum design parameter values (t, G and Gt) of the pilot plant are given in Table III. If these values are compared with those of previous studies, see Table I, it can be shown that the values of pilot plant operating parameters are within the recommended values in the previous studies. However, when baffles provided with (6×15) cm rectangular slot were used, some G values were less than 10 $sec^{-1}$; 5 out of 20 experiments for baffles arrangement No.1 and 1 out of 16 experiments for baffles arrangement No.2. The lower G values can be referred to the large cross sectional area of flow which lowers the flow velocity through the slot and, then, the velocity head and the head loss.

Table III presents, also, the ranges of water turbidity values used in baffled flocculation experiments. Where, blind baffles of 6mm tip width experiments were conducted using synthetic turbid water (STW) prepared by the addition of 1.25, 2.5, 5 and 7.5 liter kaolin stoke suspension to tap water and the remaining baffles experiments were conducted using STW prepared by the addition of 1.25 liter kaolin stoke suspension.

### *A. Flocculation Efficiency Verses Velocity Gradient*

The relationship between flocculation efficiency and velocity gradient was studied for all baffle types and arrangements. 80 experiments were conducted using blind baffles of 6mm tip width arrangement No.1. Based on results of these experiments, the relation between flocculation efficiency (FE) and G was plotted at different t values (10, 15, 20 and 25 min.) and for the 4 STWs as shown in Figs. 5 to 8. Fig.5 shows that for all t values, FE increases with the increase of G till it reaches a maximum value, then, it decreases. That can be attributed to the increase of shear force with the increase of G which can cause the breakup of flocs. The G values which produces maximum FE values vary with t; as t increases, the maximum FE occurs at lower G value. Generally, these figures show that for the same G, FE increases with the increase of t. These results agree with those of McConnachie [9].

TABLE III
OPERATING PARAMETERS OF PILOT PLANT

| **Baffles** | | **t (min.)** | | **G ($sec^{-1}$)** | | **Gt** | | **Water turbidity (NTU)** | |
|---|---|---|---|---|---|---|---|---|---|
| **Type** | **Arrang.** | **Min.** | **Max.** | **Min.** | **Max.** | **Min.** | **Max.** | **Min.** | **Max.** |
| Blind baffles of 6mm tip width | No.1 | 10 | 25 | 10.1 | 35.9 | 13842 | 24246 | 18.1 | 184.0 |
| | No.2 | 10 | 25 | 11.6 | 42.2 | 15796 | 25304 | 30.5 | 196.0 |
| Baffles have (2×15) cm rect. slot | No.1 | 10 | 25 | 10.1 | 28.4 | 13069 | 18368 | 27.7 | 53.3 |
| | No.2 | 10 | 25 | 10.0 | 27.3 | 12873 | 19309 | 22.2 | 57.1 |
| Baffles have (4×15) cm rect. slot | No.1 | 10 | 25 | 10.0 | 23.7 | 11295 | 17639 | 22.3 | 45.1 |
| | No.2 | 10 | 25 | 10.1 | 22.4 | 11666 | 16949 | 21.1 | 47.7 |
| Baffles have (6×15) cm rect. slot | No.1 | 10 | 25 | 8.2 | 22.4 | 10250 | 15574 | 23.1 | 52.5 |
| | No.2 | 10 | 25 | 8.7 | 21.0 | 10231 | 17279 | 25.8 | 89.6 |
| Baffles have circular slots of φ 2.5 cm | No.1 | 10 | 25 | 10.0 | 27.5 | 12195 | 17374 | 23.2 | 50.2 |
| | No.2 | 10 | 25 | 10.1 | 24.0 | 13396 | 17954 | 23.5 | 49.5 |
| Blind baffles of 12mm tip width | No.1 | 10 | 25 | 11.9 | 29.0 | 15042 | 20965 | 36.1 | 52.4 |
| | No.2 | 10 | 25 | 12.8 | 30.9 | 17788 | 21133 | 44.3 | 60.4 |

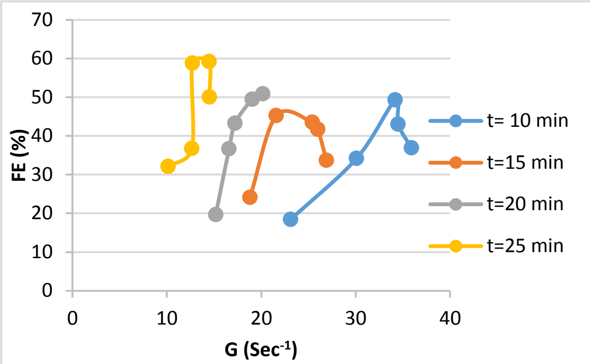



Fig.5 FE verses G at different t values for blind baffles of 6mm tip width: Arrangement No.1 with the addition of 1.25 l kaolin stoke suspension

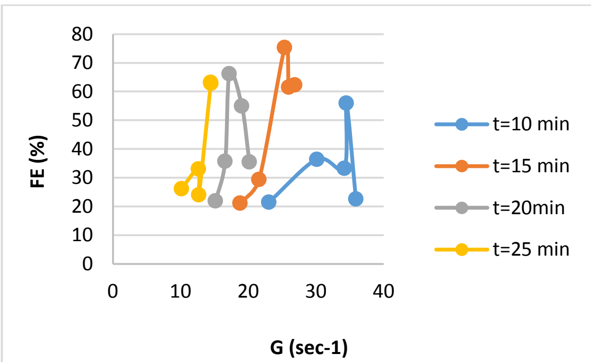



Fig.6 FE verses G at different t values for blind baffles of 6mm tip width: Arrangement No.1 with the addition of 2.5 l kaolin stoke suspension

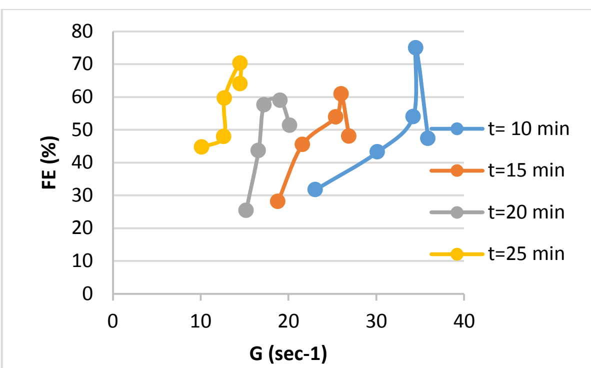



Fig.7 FE verses G at different t values for blind baffles of 6mm tip width: Arrangement No.1 with the addition of 5.0 l kaolin stoke suspension

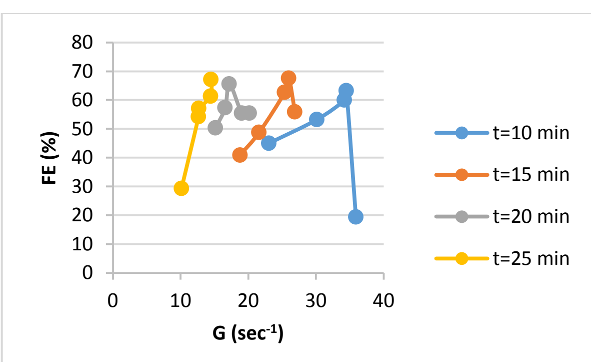



Fig.8 FE verses G at different t values for blind baffles of 6mm tip width: Arrangement No.1 with the addition of 7.5 l kaolin stoke suspension

The results of FE verses G at different t values shown in Fig.6 are similar to those shown in Fig.5 for t values of 15 and 20 min. However, inconsistent results were obtained for t values equal 10 and 25 min. The inconsistency in these results can be attributed to the uncontrolled water turbidity. Where, in spite of preparing STW by adding constant volume of kaolin stoke suspension, the water turbidity was varying according to tap water turbidity. But generally, at specific G value, FE increases with G. Also, Figs. 7 and 8 show that for specific t value, FE increases with G till it reaches maximum value, then it decreases and at specific G, FE increases with t.

64 experiments were conducted using blind baffles of 6mm tip width, arrangement No.2. Based on results of these experiments, the relation between FE and G was plotted at different t values (10, 15, 20 and 25 min.) and for the 4 STWs as shown in Figs. 9 to 12. These figures show that at t equals 25min, the ranges of G values were narrow. This can be attributed to the low head loss resulted from low flow velocity (where; maximum detention time occurs during the minimum influent flow rate). Thus, the variation in FE is mainly due to the variation of initial water turbidity. At t values of 10, 15 and 20 min., Figs.9 through 12 show that FE increases with the increase of G till it reaches a maximum value, then, it may decrease. Also, as mentioned before, the G values which produces maximum FE values vary with t. Where, as t increases, the maximum FE occurs at lower G value. Generally, these figures show that for the same G, FE increases with the increase of t.

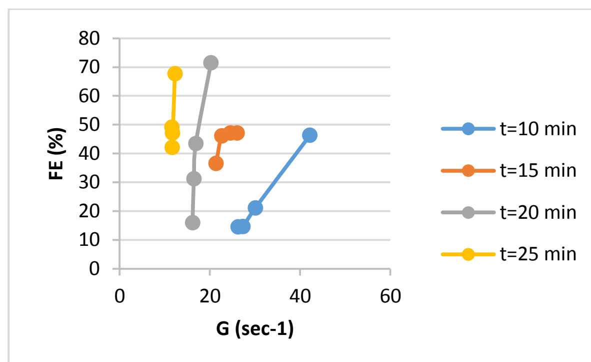



Fig.9 FE verses G at different t values for blind baffles of 6mm tip width: Arrangement No.2 with the addition of 1.25 l kaolin stoke suspension

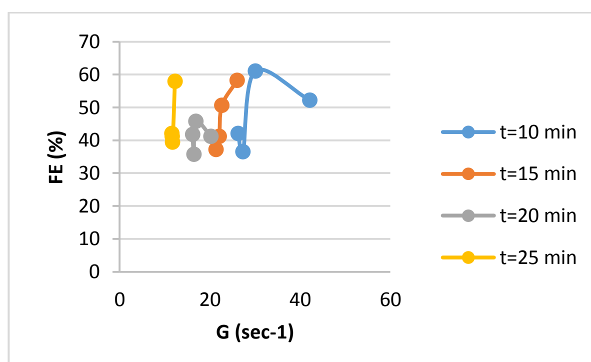



Fig.10 FE verses G at different t values for blind baffles of 6mm tip width: Arrangement No.2 with the addition of 2.5 l kaolin stoke suspension

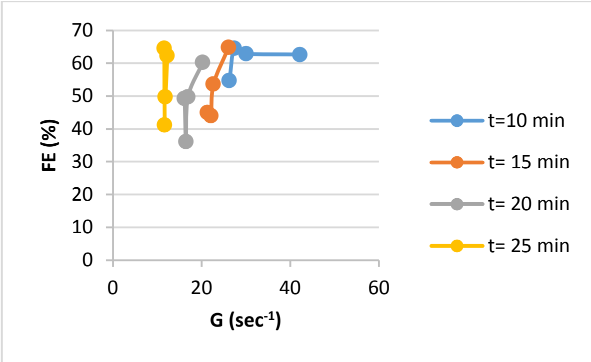



Fig.11 FE verses G at different t values for blind baffles of 6mm tip width: Arrangement No.2 with the addition of 5.0 l kaolin stoke suspension

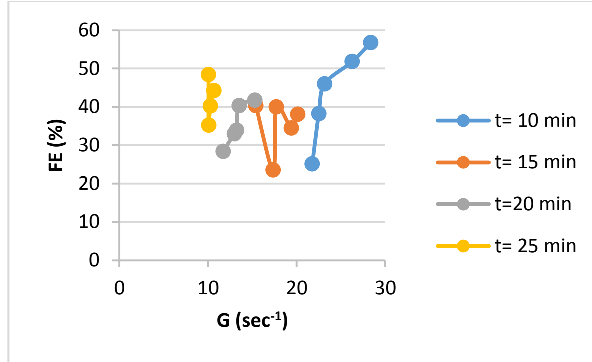



Fig.13 FE verses G at different t values for baffles have (2×15) cm rectangular slot: Arrangement No.1

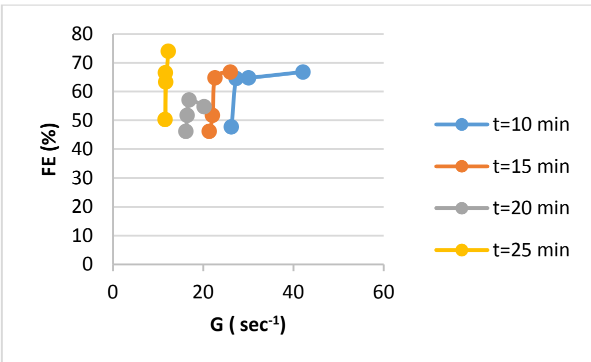



Fig.12 FE verses G at different t values for blind baffles of 6mm tip width: Arrangement No.2 with the addition of 7.5 l kaolin stoke suspension

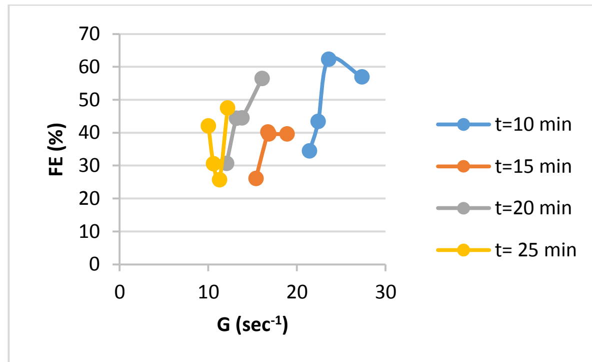



Fig.14 FE verses G at different t values for baffles have (2×15) cm rectangular slot: Arrangement No.2

20 (4 Q values× 5 NB values) flocculation experiments were conducted using baffles have rectangular slot of (2×15) cm, arrangement No.1. In addition, 16 (4 Q values× 4 NB values) flocculation experiments were conducted using the same baffles, but with adoption baffles arrangement No.2. All these 36 experiments were carried out using STW prepared by the addition of 1.25 liter of kaolin stoke suspension to tap water. Based on results of these experiments, the relation between FE and G was plotted at different t values. Figs. 13 and 14 show these relations for baffles arrangement Nos. 1 and 2, respectively. From Fig.13, it can be shown that at t equals 10 and 20min, the variation of FE with G matches that of blind baffles. However, at t equals 15 and 25 min., FE decreases with the increase of G, then, it increases. This can be explained with examining the initial turbidity values. When t equals 15min, FE equals 40.3 and 23.5 % for G and IWT values of 15.4 $sec^{-1}$ and 43.9 NTU and 17.4 $sec^{-1}$ and 27.7NTU, respectively. Thus, although G increases, IWT decreases which affects FE value. This result highlights the need for studying the impact of water turbidity on FE as will be illustrated in Section (III.C). The same result was noticed at t equals 25min., where, when G increases from 10.1 to 11.1 $sec^{-1}$, the FE decreases and this may be occurred as a result of IWT decrease. In Fig.14, when t equals 10, 15 and 20 min., the FE increases with the increase of G and as t increases the maximum FE value occurs at lower G value. However, at t equals 25min., FE decreases with the increase of G and with reading the values of IWT, it can be noticed that when G equals 10 $sec^{-1}$, the IWT was 45.8 NTU and when G equals 11.3$sec^{-1}$, the IWT was 22.2 NTU. Thus, the low FE value may be due to low IWT value.

20 (4 Q values× 5 NB values) flocculation experiments were conducted using baffles have rectangular slot of (4×15) cm, arrangement No.1. In addition, 16 (4 Q values× 4 NB values) experiments were conducted using the same baffles, but with adoption baffles arrangement No.2. All these 36 experiments were carried out using STW prepared by the addition of 1.25 liter of kaolin stoke suspension to tap water. Based on results of these experiments, the relation between FE and G was plotted at different t values. Figs. 15 and 16 show these relations for baffles arrangement Nos. 1 and 2, respectively. These figures show that at all the considered t values, the relation between FE and G matches that of blind baffles and can be explained in the same manner.

20 (4 Q values× 5 NB values) flocculation experiments were conducted using baffles have rectangular slot of (6×15) cm installed in arrangement No.1. In addition, 16 (4 Q values× 4 NB values) flocculation experiments were conducted using the same baffles, but with adoption baffles arrangement No.2. All these 36 experiments were carried out using STW prepared by the addition of 1.25 liter of kaolin stoke suspension to tap water. Based on results of these experiments, the relation between FE and G was plotted at different t values as shown in Figs.17 and 18 for

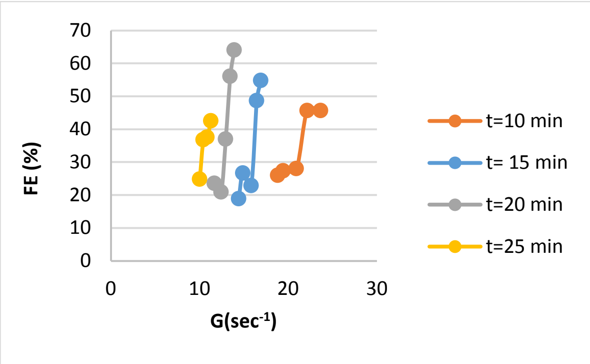



Fig.15 FE verses G at different t values for baffles have (4×15) cm rectangular slot: Arrangement No.1

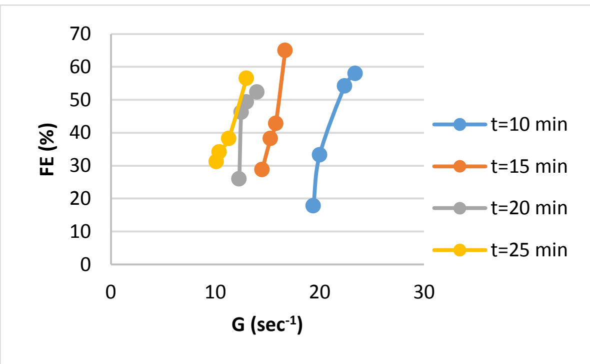



Fig.16 FE verses G at different t values for baffles have (4×15) cm rectangular slot: Arrangement No. 2

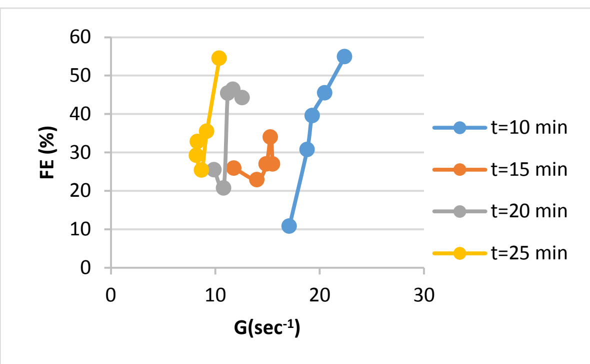



Fig.17 FE verses G at different t values for baffles have (6×15) cm rectangular slot: Arrangement No.1

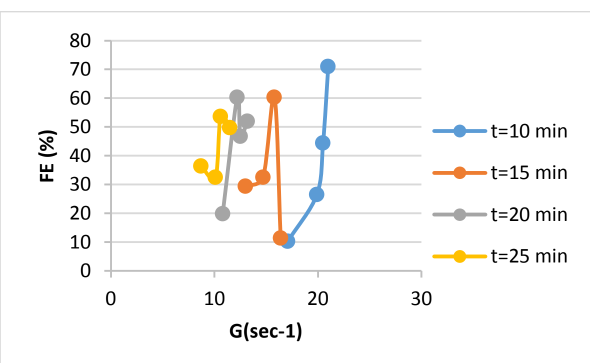



Fig.18 FE verses G at different t values for baffles have (6×15) cm rectangular slot: Arrangement No. 2

baffles arrangement Nos. 1 and 2, respectively. Generally, these figures show inconsistent FE- G relations at the different t values, but, most of results show that FE increases with G till it reaches a maximum value, then it decreases. This trend of FE variation with G may change based on IWT.

20 (4 Q values× 5 NB values) flocculation experiments were conducted using baffles have circular slots of 2.5 cm diameter installed as arrangement No.1. In addition, 16 (4 Q values× 4 NB values) flocculation experiments were conducted using the same baffles, but with adoption baffles arrangement No.2. All these 36 experiments were carried out using STW prepared by the addition of 1.25 liter of kaolin stoke suspension to tap water. Based on results of these experiments, the relation between FE and G was plotted at different t values. Fig.19 and 20 show these relations for baffles arrangement Nos. 1 and 2, respectively. Also, as the results obtained for baffles have rectangular slot of (6×15) cm, these figures show inconsistent FE- G relations at the different t values, but, most of results show that FE increases with G till it reaches a maximum value, then it decreases. This trend of FE variation with G may change based on IWT.

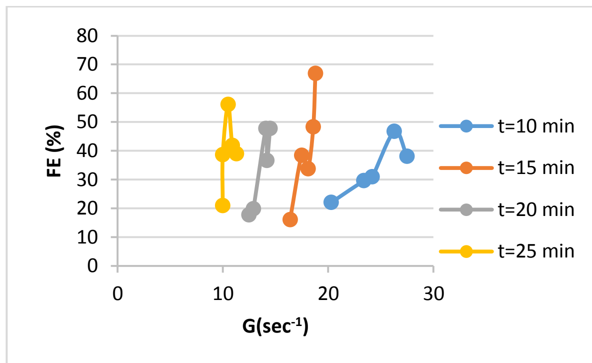



Fig.19 FE verses G at different t values for baffles have circular slots of φ 2.5 cm: Arrangement No.1

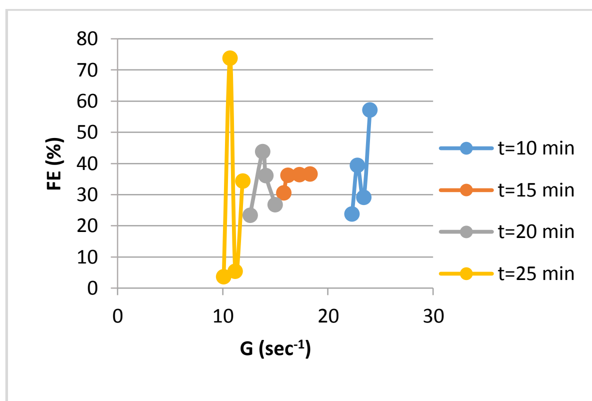



Fig.20 FE verses G at different t values for baffles have circular slots of φ 2.5 cm: Arrangement No.2

### *B. Flocculation Efficiency Verses Camp Number*

Camp number (Gt) is considered to be the most important design parameter for flocculation units. Thus, the relation between FE and Gt for baffled flocculator was examined for the different baffle shapes to study the correlation between FE and Gt. The relation of FE verses Gt was plotted for the different baffle types and volume of added kaolin solution as shown in the figures listed in Table IV. This table showes the baffle types and the corresponding figures of FE-Gt relations and the equation type of best fit curve and the values of correlation coefficient (R).

The results presented in Table IV indicate the existance of weak positive (R values between 0 and 0.3) to moderate positive (R values between 0.3 and 0.7) correleation represented by an expontial relationship between FE and Gt. That means within the Gt values range of this study (10231-25304), see Table III, FE increases with the increase of Gt but this increase varied according to baffles type and arrangement and IWT.

TABLE IV
CORRELATION ANALYSIS RESULTS OF FE AND CAMP NUMBER FOR DIFFERENT BAFFLE TYPES

| Baffles type | Arrang. | Kaolin stoke volume (l) | Fig. No. | Equation type | R |
|---|---|---|---|---|---|
| Blind baffles of 6mm tip width | No.1 | 1.25 | 21 | Exponential | 0.65 |
| | | 2.5 | 22 | Exponential | 0.61 |
| | | 5 | 23 | Exponential | 0.61 |
| | | 7.5 | 24 | Exponential | 0.67 |
| | No.2 | 1.25 | 25 | Exponential | 0.51 |
| | | 2.5 | 26 | Exponential | 0.31 |
| | | 5 | 27 | Exponential | 0.16 |
| | | 7.5 | 28 | Exponential | 0.24 |
| Baffles have (2×15) cm rect. slot | No.1 | 1.25 | 29 | Exponential | 0.25 |
| | No.2 | 1.25 | 30 | Exponential | 0.48 |
| Baffles have (4×15) cm rect. slot | No.1 | 1.25 | 31 | Exponential | 0.53 |
| | No.2 | 1.25 | 32 | Exponential | 0.53 |
| Baffles have (6×15) cm rect. slot | No.1 | 1.25 | 33 | Exponential | 0.66 |
| | No.2 | 1.25 | 34 | Exponential | 0.69 |
| Baffles have circular slots of φ 2.5 cm | No.1 | 1.25 | 35 | Exponential | 0.64 |
| | No.2 | 1.25 | 36 | Exponential | 0.11 |

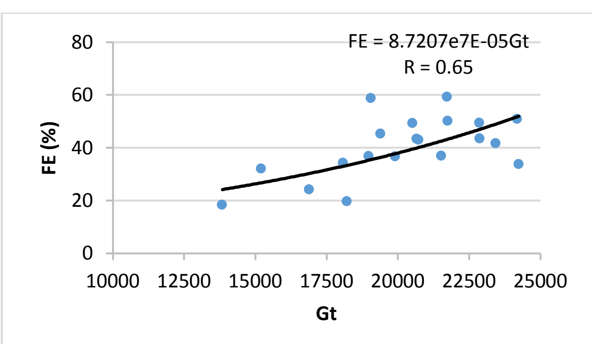



Fig.21 FE verses Gt for blind baffles of 6mm tip width: Arrangement No.1 with the addition of 1.25 l kaolin stoke suspension

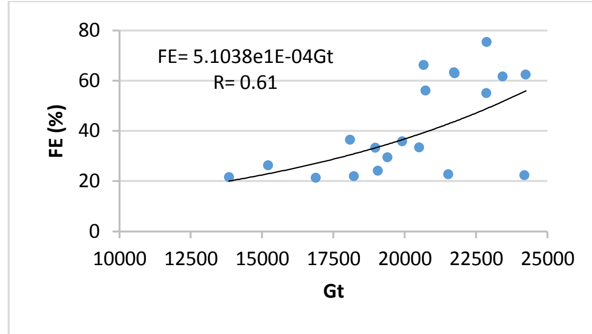



Fig.22 FE verses Gt for blind baffles of 6mm tip width: Arrangement No.1 with the addition of 2.5 l kaolin stoke suspension

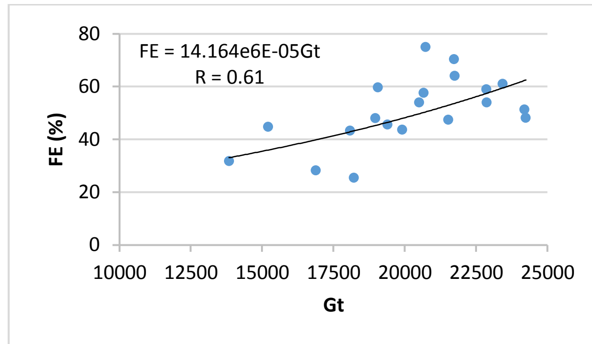



Fig.23 FE verses Gt for blind baffles of 6mm tip width: Arrangement No.1 with the addition of 5.0 l kaolin stoke suspension

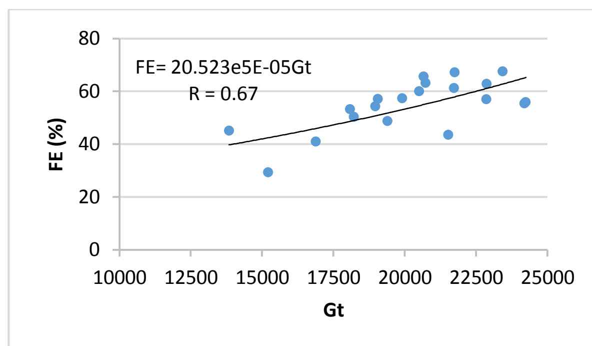



Fig.24 FE verses Gt for blind baffles of 6mm tip width: Arrangement No.1 with the addition of 7.5 l kaolin stoke suspension

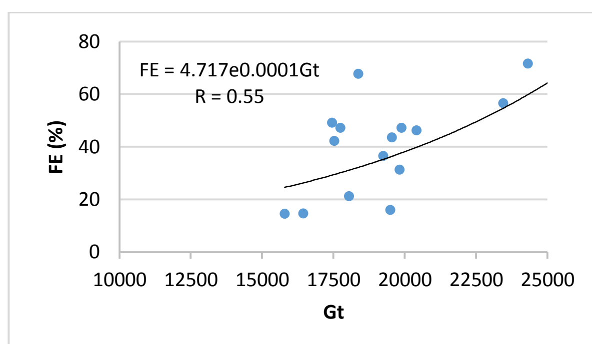



Fig.25 FE verses Gt for blind baffles of 6mm tip width: Arrangement No.2 with the addition of 1.25 l kaolin stoke suspension

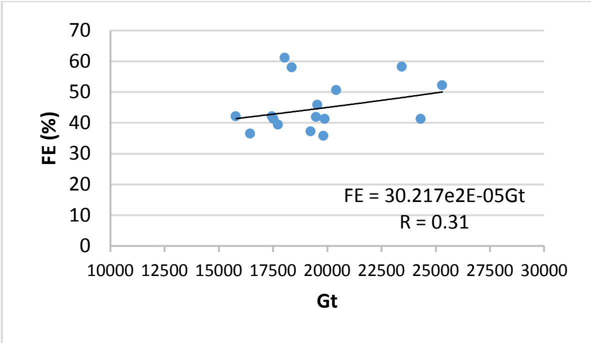



Fig.26 FE verses Gt for blind baffles of 6mm tip width: Arrangement No.2 with the addition of 2.5 l kaolin stoke suspension

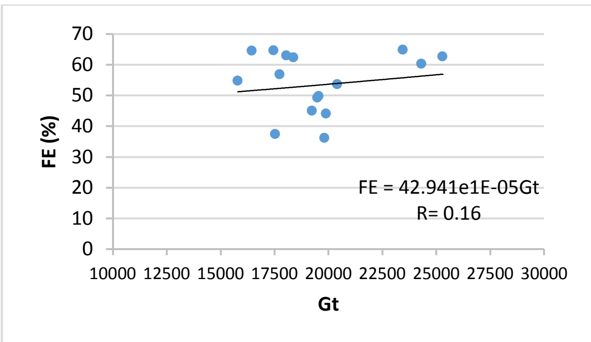



Fig.27 FE verses Gt for blind baffles of 6mm tip width: Arrangement No.2 with the addition of 5.0 l kaolin stoke suspension

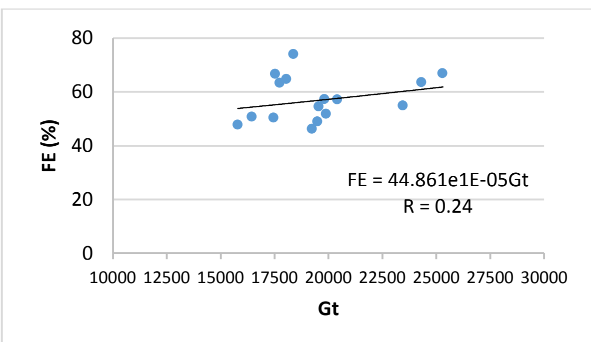



Fig.28 FE verses Gt for blind baffles of 6mm tip width: Arrangement No.2 with the addition of 7.5 l kaolin stoke suspension

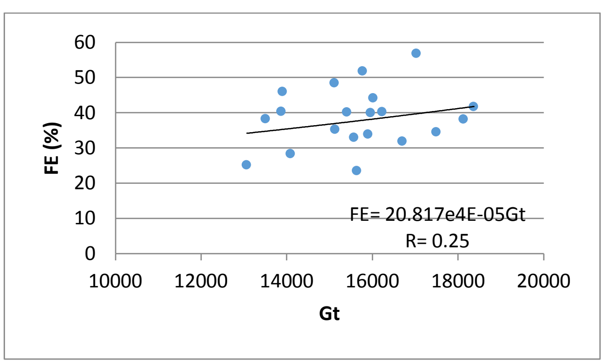



Fig.29 FE verses Gt for baffles have rectangular slot of (2×15) cm: Arrangement No.1

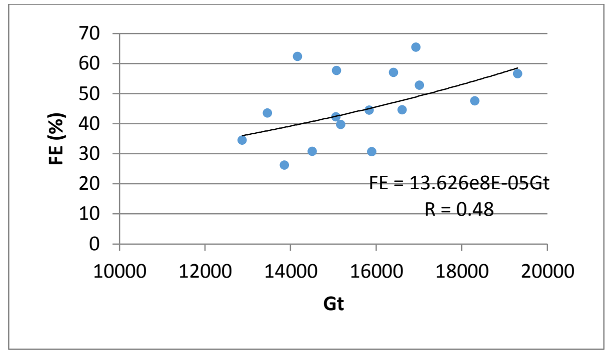



Fig.30 FE verses Gt for baffles have rectangular slot of (2×15) cm: Arrangement No.2

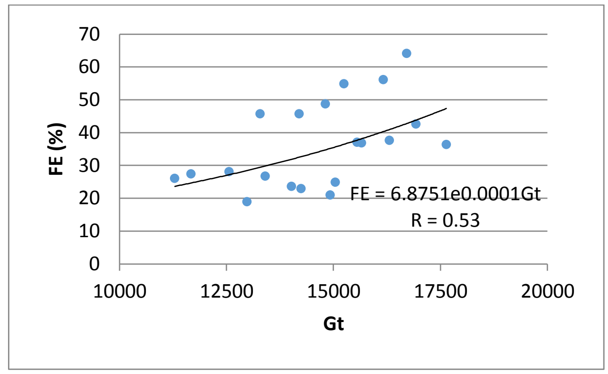



Fig.31 FE verses Gt for baffles have rectangular slot of (4×15) cm: Arrangement No.1

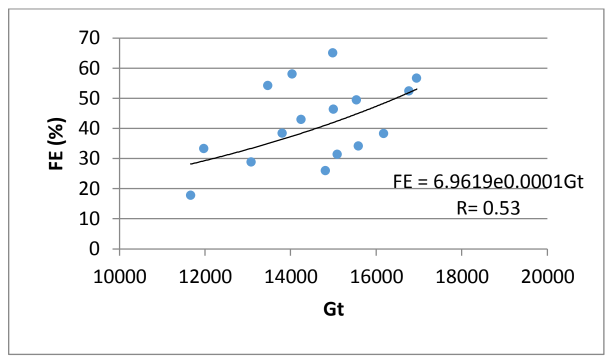



Fig.32 FE verses Gt for baffles have rectangular slot of (4×15) cm: Arrangement No.2

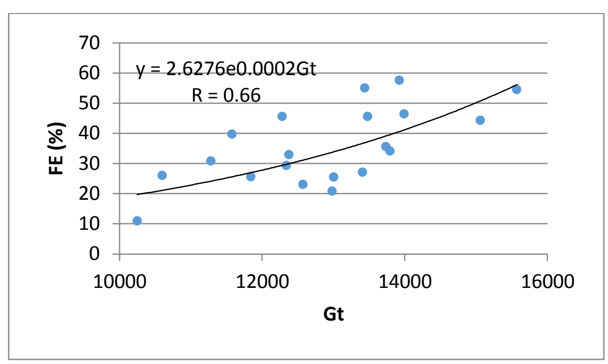



Fig.33 FE verses Gt for baffles have rectangular slot of (6×15) cm: Arrangement No.1

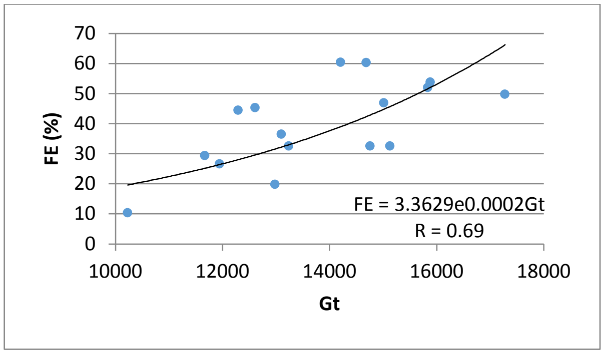



Fig.34 FE verses Gt for baffles have rectangular slot of (6×15) cm: Arrangement No.2

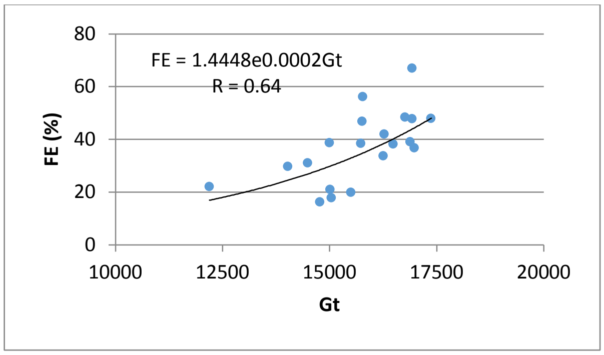



Fig.35 FE verses Gt for baffles have circular slots of φ 2.5cm: Arrangement No.1

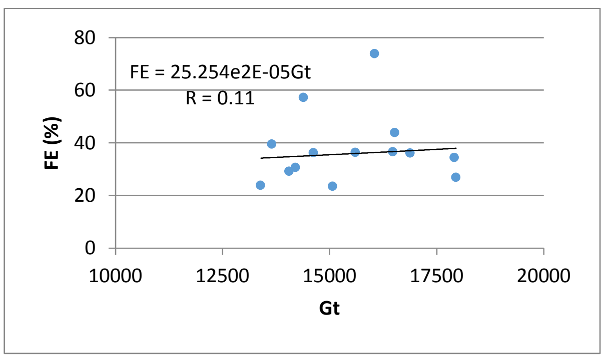



Fig.36 FE verses Gt for baffles have circular slots of φ 2.5cm: Arrangement No.2

### *C. Dependency of Flocculation Efficiency on Water Turbidity*

From the results presented in Section (III.A), it was found that the IWT of water has an impact on FE of the baffled flocculators. To study the correlation of FE and IWT, the relationship between them has been plotted for the considered baffles types and arrangements. These relations are shown in the figures listed in Table V. This table showes the baffle types and the corresponding figures of FE-IWT relations and the equation type of best fit curve and the R values.

The most comprehensive results used for plotting FE-IWT relations were obtained from flocculation experiments conducted using blind baffles. That was because these experiments were conducted using STW prepared by the addition of 4 dosages of kaolin stoke suspension to tap water. However, although, the experiments of the other baffle shapes were carried out using STW prepared by adding one dosage of kaolin stoke suspension to tap water, the turbidity of this STW varied from one experiment to another due to the variation of tap water turbidity. In these experiments, the initial turbidity values varied within narrow ranges as compared with those of blind baffles experiments as presented in Table III.

The results presented in Table V indicate the existance of weak positive to good positive correleations represented by logarithmic relationship between FE and IWT. That means within the IWT values range of this study (18.1-196) NTU, see Table III, FE increases with the increase of IWT but this increase varied according to baffles type and arrangement. This result can be explained as; as water turbidity increases the suspension is more dense and, thus, the distances between the suspended solid particles will be small which increases the chance for particles collisions and subsequently flocs growth. The increase of FE with IWT was noticed, also, by Liu et al. [14] who considered around-the-ends baffled flocculator.

TABLE V
CORRELATION ANALYSIS RESULTS OF FE AND IWT FOR DIFFERENT BAFFLE TYPES

| Baffle type | Arrang. | Fig. No. | Equation type | R |
|---|---|---|---|---|
| Blind baffles of 6mm tip width | No.1 | 37 | Logarithmic | 0.48 |
| | No.2 | 38 | Logarithmic | 0.65 |
| Baffles have (2×15) cm rectangular slot | No.1 | 39 | Logarithmic | 0.30 |
| | No.2 | 40 | Logarithmic | 0.07 |
| Baffles have (4×15) cm rectangular slot | No.1 | 41 | Logarithmic | 0.26 |
| | No.2 | 42 | Logarithmic | 0.56 |
| Baffles have (6×15) cm rectangular slot | No.1 | 43 | Logarithmic | 0.40 |
| | No.2 | 44 | Logarithmic | 0.67 |
| Baffles have circular slots of φ 2.5 cm | No.1 | 45 | Logarithmic | 0.67 |
| | No.2 | 46 | Logarithmic | 0.74 |

It is important to mention here that in real water treatment plants, the raw water turbidity is dependent on the characteristics of water source and thus it cannot be controlled as in the present in this study. That means, the performance of flocculation process will vary according to raw water turbidity in addition to the controlled design parameters (t, G and Gt).

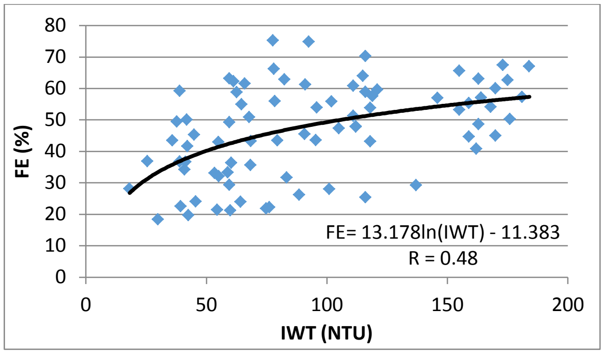



Fig.37 FE verses IWT for blind baffles of 6mm tip width: Arrangement No.1

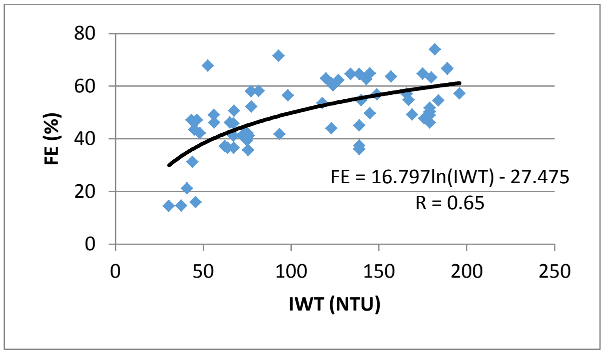



Fig.38 FE verses IWT for blind baffles of 6mm tip width: Arrangement No.2

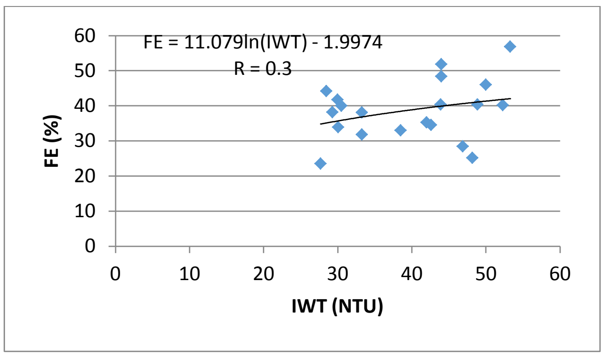



Fig.39 FE verses IWT for baffles have rectangular slot of (2×15) cm: Arrangement No.1

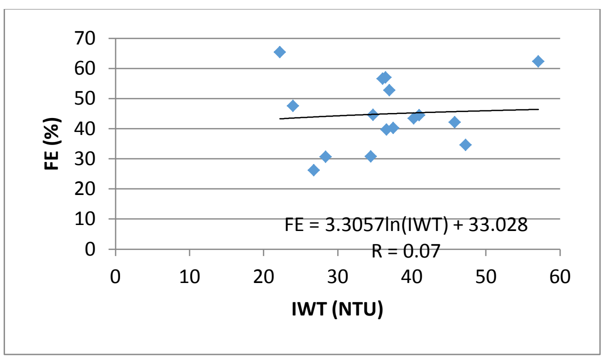



Fig.40 FE verses IWT for baffles have rectangular slot of (2×15) cm: Arrangement No.2

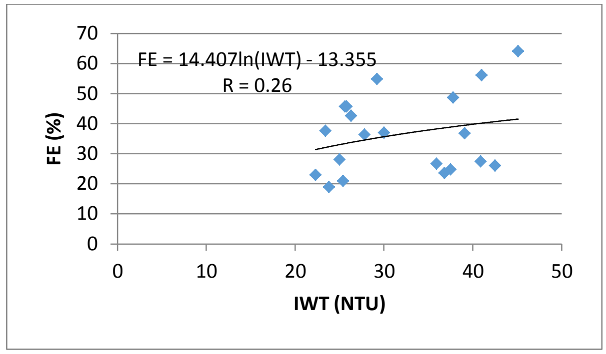



Fig.41 FE verses IWT for baffles have rectangular slot of (4×15) cm: Arrangement No.1

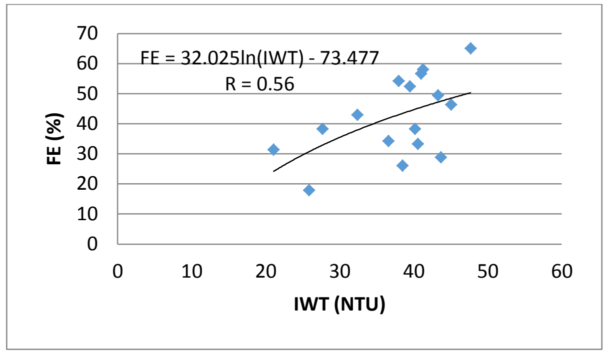



Fig.42 FE verses IWT for baffles have rectangular slot of (4×15) cm: Arrangement No.2

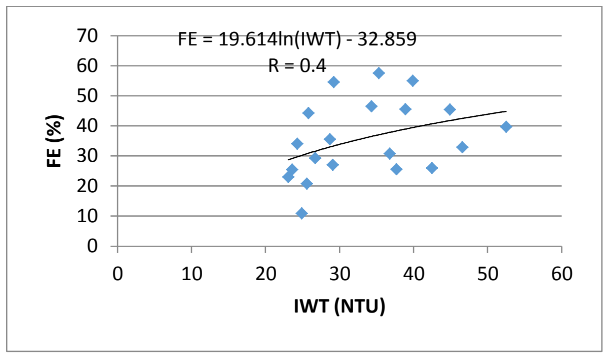



Fig.43 FE verses IWT for baffles have rectangular slot of (6×15) cm: Arrangement No.1

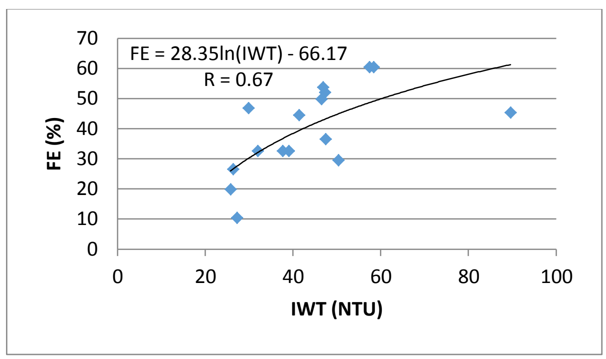



Fig.44 FE verses IWT for baffles have rectangular slot of (6×15) cm: Arrangement No.2

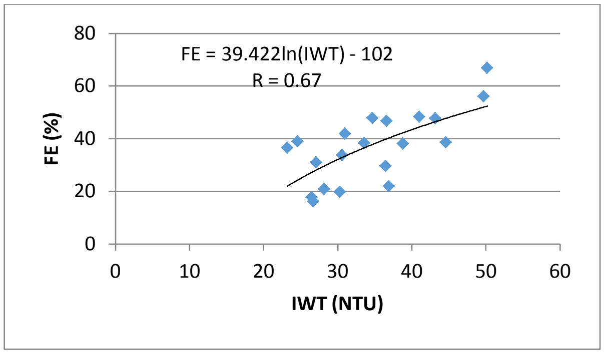



Fig.45 FE verses IWT for baffles have circular slots: Arrangement No.1

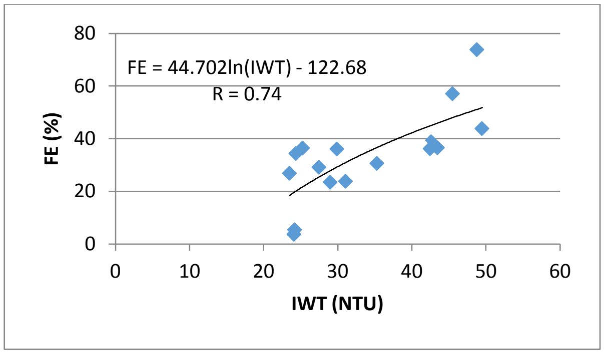



Fig.46 FE verses IWT for baffles have circular slots: Arrangement No.2

*D. Baffles Shape and Configuration Effect on Flocculation Efficiency*

From the above results, it was found that the performance of baffled flocculation tank provided with specific baffles type and arrangement is dependent on design parameters (t, G and Gt) in addition to raw water turbidity. But since the main aim of this thesis is studying the effect of baffles shapes and configuration (arrangement) on flocculation efficiency, the maximum FE values obtained using the different baffle shapes for arrangement No.1 and 2 were compared at different number of baffles. The comparison results are shown on Figs.47 and 48 for arrangement Nos.1 and 2, respectively.

For baffles arrangement No.1, Fig.47 shows that the blind baffles type gives the highest values of FE for all NB values as compared with the other baffle types. For NB values of 5 and 10, and according to descending order of FE values, the order of the other baffle types is; baffles of (2×15) cm rectangular slot, baffles of (4×15) cm rectangular slot, baffles of (6×15) cm rectangular slot and baffles of circular slots. For the other NB values, there is no clear order of FE values.

For baffles arrangement No.2, Fig.48 shows that the blind baffles type gives the highest values of FE for NB values of 5, 15 and 20 as compared with the other baffle types. At NB of 10, baffles of circular slots have the highest FE value. For the other baffle types, there is no clear order of FE values.

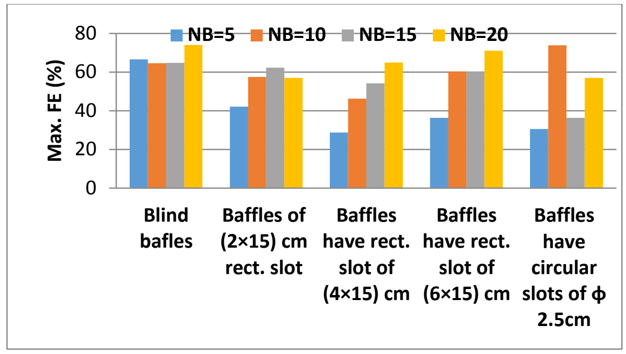



Fig.47 Maximum FE verses baffles shape at different NB values for arrangement No.1

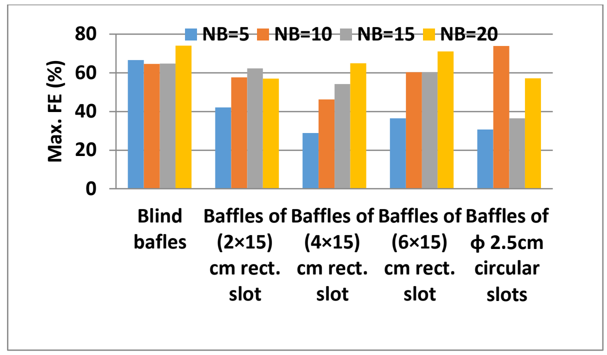
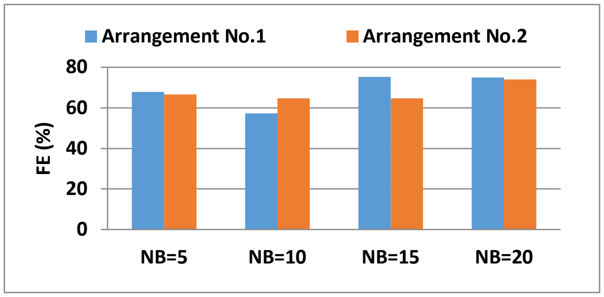


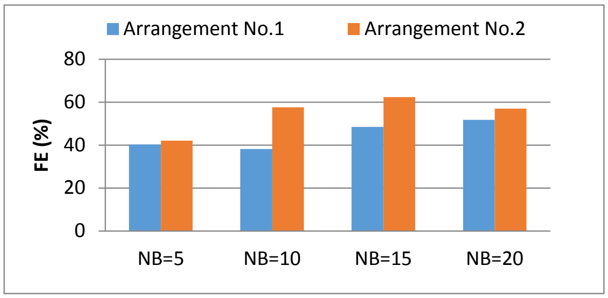

Fig.48 Maximum FE verses baffles shape at different NB values for arrangement No.2

To study the effect of baffles arrangement on baffled FE, the values of maximum FE verses NB for arrangement No.1 were compared with those of arrangement No.2 at all the considered baffle shapes. The comparison results are shown in Fig. 49. From Fig.49-a, it can be shown that FE values of blind baffles-arrangement No.1 for NB equals 5, 15 and 20 are higher than those of arrangement No.2. In contrast, the FE value for NB of 10 is higher for arrangement No.2. For baffles of (2×15), (4×15) or (6×15) cm rectangular slot, Figs.49; b, c and d show that arrangement No.2 gives higher FE values than those of arrangement No.1 at all NB values. In case of baffles of circular slots, Fig.49-e shows that at NB equals 5, 10 and 20, FE values for arrangement No.2 are higher than those of arrangement No.1. In contrast, the FE value for NB of 15 is higher for arrangement No.1.

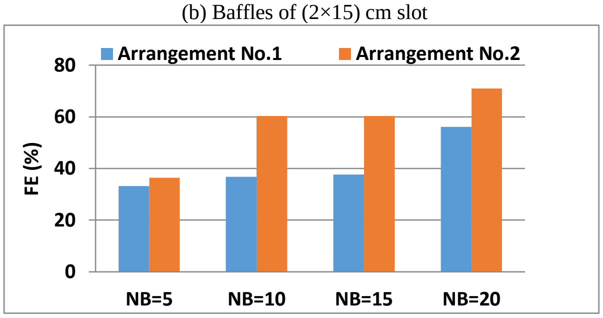
From the above results it can be shown that the deciding of baffles number during the design stage of baffled flocculation unit is not adequate to guarantee its best performance. That is because FE can be affected by baffles arrangement. Thus, it is necessary to examine the performance of the proposed baffled flocculation unit using a pilot plant or CFD modeling technique.



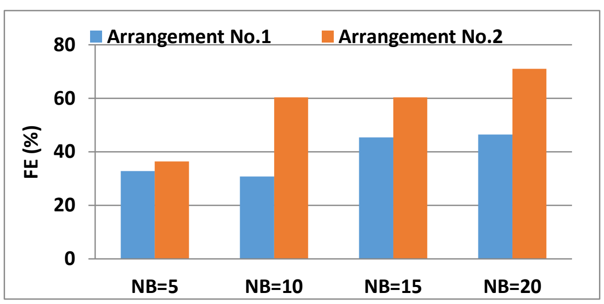

(a) Blind baffles



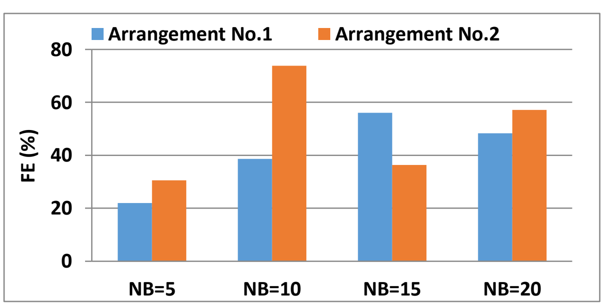

(b) Baffles of (2×15) cm slot




(c) Baffles of (4×15) cm slot




(d) Baffles of (6×15) cm slot




(e) Baffles of circular slots

Fig.49 Baffles arrangement effect on max. FE for different baffle shapes

### E. *Head Loss Coefficient*

In designing, baffled flocculation tanks, the tank capacity is calculated using Eq. (1) after assuming t value within the range of design criteria. The number of baffles is obtained using Eq. (4) where the head loss coefficient (k) is assumed using the values cited in literature and the head loss is obtained from Eq. (2) after assuming G value within the range of design criteria. That means it is important to select the appropriate k value, since the baffles number affects G value and, then, FE.

In this study, k value was determined for each flocculation experiment of all baffle types and arrangements. That was done using Eq. (4) with putting the used NB, the calculated flow velocity (measured influent flow rate divided by cross sectional area of slot) and the measured head loss corresponding to NB. Also, statistical analysis was carried out to specify the minimum and maximum k values for each baffle type and arrangement and the range of most frequent k values. The range of most frequent k values was determined by drawing the histogram of k distribution using EXCEL software. The minimum, maximum and most frequent values of K are given in Table VI for the considered baffles shapes and arrangement.

TABLE VI
HEAD LOSS COEFFICIENT ACCORDING TO SHAPE AND ARRANGEMENT OF BAFFLES

| **Baffles** | | **K** | | |
|---|---|---|---|---|
| **Type** | **Arrang.** | **Min. value** | **Max. value** | **Range of most frequent values** |
| Blind baffles of 6mm tip width | No.1 | 0.9 | 6.3 | 2-2.5 |
| | No.2 | 0.9 | 6.8 | 2-2.5 |
| Baffles of (2×15) cm rectangular slot | No.1 | 0.5 | 5.1 | 1-1.5 |
| | No.2 | 0.6 | 5.1 | 0.5-1 |
| Baffles of (4×15) cm rectangular slot | No.1 | 1.4 | 20.4 | 1.0-3.0 |
| | No.2 | 1.6 | 20.4 | 3.0-5.0 |
| Baffles of (6×15) cm rectangular slot | No.1 | 2.8 | 30.7 | 9.5-11.5 |
| | No.2 | 3.2 | 34.5 | 15.5-17.5 |

## IV. CONCLUSIONS

Based on results of 304 flocculation experiments conducted in this study using a pilot plant of baffled flocculator, the following conclusions were drawn:

1. For all the baffle types and arrangements, FE increases with the increase of G till it reaches a maximum value, then, it decreases.
2. For all the baffle types and arrangements, as detention time increases, the maximum FE occurs at lower G value.
3. Within the adopted range of Gt values (10231-25304), FE increases with the increase of Gt but this increase varied according to baffles type and arrangement and

water turbidity. The correlation between FE and Gt for the different baffles types is weak to moderate positive (R=0.11 to 0.69).

4. Within the adopted range of IWT values (18.1-196) NTU, FE increases with the increase of IWT but this increase varied according to baffles type and arrangement.The correlation between FE and IWT for the different baffles types is weak positive to good positive represented by logarithmic relationship (R= 0.07-0.74).
5. Within the implemented baffle types, the blind baffles type gives the highest values of FE for all the number of baffles as compared with the other baffle types.
6. The deciding of baffles number during the design stage of baffled flocculation unit is not adequate to guarantee its best performance and it is necessary to examine the performance of the proposed baffled flocculation unit using a pilot plant or CFD modeling technique.
7. The value of head loss coefficient depends mainly on baffles type.

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