International Journal of Modern Engineering Research (IJMER)
www.ijmer.com Vol.2, Issue.4, July-Aug 2012 pp-1534-1539 ISSN: 2249-6645

Experimental and Numerical Analysis On Horizontal Jet Flocculates For Small Water Supply Schemes

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ABSTRACT: It is often seen that conventional water treatment plants are not necessarily cost effective, specifically for smaller units up to 3 MLD. The flocculator is an important unit of the water treatment plant and more often fitted with mechanical stirrers or vanes. The problems associated with maintenance and running of the mechanical components impose a severe constraint on such units, specifically in developing countries of Asia Pacific region. It is therefore necessary to explore and find other simpler devices free from such constraints. The jet flocculator seems to be a viable alternative. Guidelines for preliminary design of a jet flocculator are not available even though it is simple, economical and robust to operate. The present investigation is to study the performance of single-basin jet flocculators using both experimental and numerical techniques. A number of performance indices, some already existing and some new, are being made use of in assessing the performance of the flocculator.

KEYWORDS: Experimental, Numerical Analysis, Horizontal Jet Flocculators, Small Water Supply Schemes

I. INTRODUCTION

Coagulation and flocculation are the water treatment process by which finely divided suspended and colloidal matter in the water is made to agglomerate and form flocs. This enables their removal by sedimentation, dissolved air flotation or filtration. Colloidal particles (colloids) are midway in size between dissolved solids and suspended matter. Colloids are kept in suspension (stabilized) by electrostatic repulsion and hydration. Electrostatic repulsion occurs because colloids usually have a surface charge due to the presence of a double layer of ions around each particle. Thus, the colloid has an electric charge, mostly a negative one. Hydration is the reaction of particles at their surface with the surrounding water. The resulting particle-water agglomerates have a specific gravity, which differs little from that of water itself.

The electrostatic repulsion between colloidal particles effectively cancels out the electronic attraction forces (Van der Waals' forces) that would attach the particles together. Certain chemicals (called coagulating agents, coagulants) have the capacity to compress the double layer of ions around the colloidal particles. They reduce the range of the electrostatic repulsion, and thus enable the particles to flocculate, i.e. to form flocs. These flocs can grow to a sufficient size and specific weight to allow their removal by settling, flotation or filtration. Generally water treatment processes involving the use of chemicals are not so suitable for small community water supplies. They should be avoided whenever possible. Chemical coagulation and flocculation should only be used when the needed treatment result cannot be achieved with another treatment process using no chemicals. If the turbidity and colour of the raw water are not much higher than is permissible for drinking water, it should be possible to avoid chemical coagulation in the treatment of the water. A process such as slow sand filtration or multi-stage filtration would serve both to reduce the turbidity and colour to acceptable levels, and to improve the other water quality characteristics, in a single unit. A roughing filter can serve to reduce the turbidity load on the slow sand filter, if necessary. .

Flocculation is the process of gentle and continuous stirring of coagulated water for the purpose of forming flocs through the aggregation of the minute particles present in the water. It is thus the conditioning of water to form flocs that can be readily removed by settling, dissolved air flotation or filtration. The efficiency of the flocculation process is largely determined by the number of collisions between the minute coagulated particles per unit of time. There are mechanical and hydraulic flocculators. In mechanical flocculators the stirring of the water is achieved with devices such as paddles, paddle reels or rakes. These devices can be fitted to a vertical or horizontal shaft. Vertical shaft flocculators are usually placed in a square tank with several chambers (four or more). They have the advantage of having only bearing in the water, and no gland is necessary as the motor and gearing are above the water. With horizontal shaft flocculators having a traverse flow, one should provide at least four rows of shafts, with partitions of baffles (stop logs), so as to avoid short-circuiting. In hydraulic flocculators the flow of the water is so influenced by small hydraulic structures that a stirring action results. Typical examples are channels with baffles, flocculator chambers placed in series (e.g. *Alabama*-type flocculator) and gravel bed flocculators.

Their advantages are that they have no motor power, electric cables switchgear, etc. to maintain and general maintenance is easier.Mechanical and hydraulic methods are often used to create an agitation in the flocculation chamber thereby maintaining a velocity gradient. This stage is called the orthokinetic flocculation.

II. Present Scenario

As per the performance evaluation survey conducted by National Environmental Engineering Research Institute (NEERI), Nagpur during 1988-89 on 51 water treatment plants in India, it was found that effective supervision and managerial control are absent in most of the plants (Mhaisalkar and Tidke, 1998). Only 39% of the plants were producing quality water meeting the CPHEEO standards. The reasons quoted for this poor performance are the lack of funds for operation and maintenance, non-availability of spare parts, untrained laboratory staff, poor administration, negligence by the staff and improper co-ordination between the staff. Conventional water treatment plants are not necessarily cost effective, specifically for smaller unit of capacity up to 3 MLD. The flocculator is an all important unit of the water treatment plant and more often fitted with mechanical stirrers or vanes. The problems associated with maintenance and running of the mechanical components impose a severe constraint on such units, specifically in developing countries of Asia Pacific region. It is therefore necessary to explore and find other simpler devices free from such constraints. The jet flocculator seems to be a viable alternative. Guidelines for preliminary design of a jet flocculator are not available even though it is simple, economical and robust to operate.

III. OBJECTIVE OF THE STUDY

The present investigation is to study the performance of single-basin jet flocculators using both experimental and numerical techniques. A number of performance indices, some already existing and some new, are being made use of in assessing the performance of the flocculator.

IV. MATERIALS AND METHODS

4.1EXPERIMENTAL SETUP

The main components of the set-up consisted of a tank to store the turbid water, a constant head supply chamber, supply pipeline fitted with pressure taps and a bypass pipe, an orifice meter in the supply line to aid mixing of coagulants injected into it by a peristaltic pump, manometers, flocculation chamber having a nozzle fitted at the inlet end and a suitable overflow mechanism at the outlet end. Preparation of the turbid water was quite crucial since the synthetically generated turbidity should be quite close to the natural condition. Turbid water in nature contains particles of different sizes and specific gravity. As observed by Hudson (1965), most particles causing turbidity in natural channels are smaller than 10 mm while a majority is smaller than 1.5 mm. Throughout the present experimentation, Bentonite was used to generate different levels of turbidity of 100 , 50 and 25 NTU.

Tap water available in the laboratory had a turbidity of less than 0.9 NTU. The amount of Bentonite required to generate different intensities of turbidity in a sample was found to vary in a linear fashion,

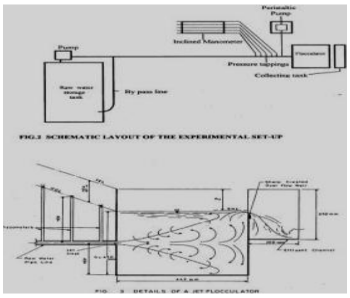

Figure.1 Schematic Layout Of Experimental Setup

Bentonite in mg/L = 1.5857 x turbidity in NTU – 1.4271

Standard jar-tests were carried out with the objective of estimating the optimum concentration of the Alum needed for removal of the suspended matter. The optimal Alum dosage (in mg/L) necessary to treat raw water was 44.50, 36.00, and 34.00 for turbidity intensities of 100 NTU, 50 NTU and 25 NTU respectively.

Raw-water alkalinity (CaCO3 in mg/L) was noted every day before the start of the experiment and was found to be almost the same, 40 mg/L, throughout the period of experimentation. However, addition of the coagulant altered the alkalinity. Samples of water taken from the jar for the highest dosage of the Alum used in this investigation had alkalinity in excess of 10 mg/L, sufficient not to hinder the formation of flocs. Similarly, other characteristics of water, especially, the pH values have a considerable influence on the satisfactory formation of flocs. In the present investigation the pH of the synthetic turbid water was in the range of 6.8 to 7.0. The recommended pH zone while using Alum as a coagulant is 6.5 to 7.5. The two ranges being not very different, no additional chemical was used in the experiments to control the pH level. The temperature of raw water in the experiments was in the range 27^0C to 28^0C.

4.2 EXPERIMENTAL PROCEDURE

Flocculation chambers having identical capacities but of different plan shapes were fabricated out of metalic sheets and red oxide priming coat was applied to avoid any chemical reaction of the alum with the metal surface. Raw water stored in a tank was pumped to the flocculator with the help of a pump. The required flow rate was setup by adjusting the valves provided on the main and bypass pipe lines. The flow from the inlet to the flocculator was in the form of a jet emanating from a submerged pipe. The rate of flow entering and leaving the flocculator was measured volumetrically using a collecting tank. To ensure proper mixing of the coagulant with raw water, alum solution was injected as a co-current axial jet into the raw water supply line 1.5m ahead of the jet nozzle with the help of a peristaltic pump. The peristaltic pump discharge was calibrated to improve the accuracy of the results. The flow rate and the operation time parameter of the peristaltic pump were pre-set at the desired values. To determine the total energy on the up-stream side of the flocculator 3 pressure tappings of 1mm diameter were provided at a space of 27cm center to center on the pipe line leading to the flocculator. All pressure head measurements were made with reference to the center line of the influent pipe to the flocculator. A manometer connected to these tappings was supported by a board, and a scale readable to the nearest 1mm of water was provided. For proper mixing, Holland and Chapman (1966) recommended that the liquid level in the tank should be less than 1.25 times the highest lateral dimension of the tank so as to avoid multiple impellers or excessive power consumption. Van De Vasse (1955) observed that the circulation pattern established by a jet system is similar to that established by a propeller stirrer. Hence a jet submergence depth equal to 50% of liquid depth was adopted as a reference value.

Experiments were conducted with a rectangular and circular flocculation chamber for different jet sizes of 8, 10, 12, and 15mm in diameter. Hydraulic retention time equal to 6, 7.5, 10, 15 and 20 minutes were selected while repeating the experiments. Experiments repeated for alternative outflow sections. A digital pH-meter was used to determine the pH values of the raw water. Similarly, turbidity meters were calibrated with a standard suspension. In the Nephelometric method followed here, a comparison of the intensity of light scattered by the sample under specified conditions was made with the intensity of light scattered by a standard reference suspension. The least count of the turbidity meter was 0.1 NTU.

To study the distribution of residence time of the tracer, laboratory grade common salt was used as atracer and a digital conductivity meter having a least count of 0.1 micromhos/cm was used to measure conductivity of the solution. The meter was calibrated at the test temperature of 26^{0}c and the conductivity of water was displayed directly and a best fit relationship $Y = 0.56X - 32.50$ was obtained.Y is the sodium concentration in mg/l and X is the conductivity in micromhos/cm. For a selected detention time, weight of salt equivalent to the weight of water passing per minute multiplied by 500 ppm was dissolved in water and it was injected using a peristaltic pump. The requisite amount of tracer solution was injected as a co–flowing axial jet at a section little ahead of the jet efflux section as a slug dossage over a time span of one minute depending on the flow rate. After the injection of salt solution, samples were collected at the outlet of the weir initially at 0.5, 1, 2, 3, 4 minutes and thereafter for every 1/5 of nominal detention time in minutes.

The samples were collected till the tracer disappeared from the collected sample. The sodium concentration at the chamber outlet was determined as a function of time with the help of digital conductivity meter. Based on the measured conductivity of the sample, the concentration of sodium chloride was worked out from the calibration curve corresponding to the test temperature. For every tracer experiment, a separate calibration chart was prepared before commencing the experiment. Material balance check was performed to verify that the recovery of entire tracer balances with the quantity added at the beginning of the flow (Hudson, 1981). The area lying under the normalized time distribution curve indicated this.

The turbidity meter, submersible pump and the peristaltic pump were always calibrated just before the start of an experiment. The dimensions of flocculation chambers are presented in Table.1. The volume of all the basins were 0.0883 m^3 and a liquid depth of 45cm was maintained in all the chambers. The type of outlet in basin A and B was weir type, whereas the C type outlet was a circular opening of size 50 mm in diameter. Though, all alternative basin layouts were adopted for numerical simulation of the flow field and dispersion of tracers, some amongst them were only selected for experimentation on flocculation and turbidity removal efficiency. It should be realized that ultimate performance of a flocculator depends upon both coagulation and flocculation. Hence, it will be meaningful to segregate the effect of rapid mixing to assess properly the role of different design parameters on the performance of a flocculation chamber. It was observed that as long as the GT values of the rapid mixing device lay in the range of 10,600 and 18,800 the performance of the flocculation chamber remained unaffected. Hence, in all the flocculation experiments of the present study, care was exercised to maintain the GT of rapid mixing within the said range. For each of the flocculator basins under consideration, on adding the coagulant the residual turbidity reached a steady state value after lapse of four to five times the theoretical retention time, T = (volume of the basin)/(flow rate Q). Hence in all the flocculation experiments floc-laden water samples were collected in settling jars at the outlet of the flocculator only after a lapse of 5.5 times the residence time. The samples were allowed to settle for a period of 30 min in settling jars before measuring the residual turbidity. The recommented plan area of jar is 115 x 115mm with a liquid depth of 210mm (Gregory R., et al., 1990). Further it has been specified that the outlet for the withdrawal of the sample should be 100mm below the liquid level.The turbidity of the settled water was measured by a nephelometric turbimeter and an average of three samples tested is reported.

Table.1 Dimension Of Flocculator Basins

Basin no.	L mm	W mm	H (depth of water) mm
	443	443	450
2	Circular basin with D=500mm and H=450mm		

V. Result & Discussion

Result of floc and tracer studies

The results observed while conducting floc and tracer studies on 100, 50 and 25NTU turbid water have been observed for different sizes of jet diffusing in rectangular and circular chambers with alternative outlets.

4.2 HYDRAULIC RETENTION TIME

Figure 2 shows Effect Of Hydraulic Retention Time On Turbidity Removal

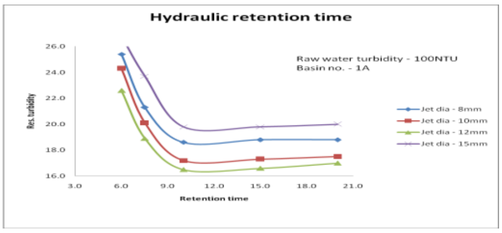

FIGURE.2 EFFECT OF HYDRAULIC RETENTION TIME ON TURBIDITY REMOVAL

Experiments were conducted with basin 1A for two different jet sizes of 8 , 10, 12 and 15mm in diameter. Retention time equal to 6, 7.5, 10, 15 and 20 min were selected while repeating the experiments. Parameters like Camp number for rapid mixing (GT = 10660), coagulant dosage (44.5 mg/L), influent raw-water turbidity (100 NTU), total alkalinity (40 mg/L of CaCO3) and pH (6.8-7.0) value were held constant in all the trials. The variation in the residual turbidity as a function of the retention time is shown in Fig.. For different sizes of the nozzles used, the improvement in the performance of the flocculation tank is insignificant for a retention time exceeding 10 min. The same was also observed to hold good in case of the 50 NTU and 25NTU turbid water experiments. Hence, for free-jet-flocculators a retention time of 10 min may be sufficient. It is worth noting that this is only a fraction of the retention time of 30 min, normally recommended for flocculators having mechanical devices.

From the above one can notice that the jets 10mm and 12mm in diameter, performs marginally better than the 8 and 15mm diameter jets even though it has smaller values for G and GT. This highlights the fact that the performance of the flocculator is not sensitive to the G and GT values, specifically when they are in the range of 30 & 85 s^{-1} and 23,000 & 50,000 respectively.

The results of experiments on rectangular basin no. 1A, 1B, and 1C considering Camp's number, GT, as the guiding factor are shown in Table for different sizes of the jet diffusing in rectangular and circular tanks. Influent raw water turbidity of No = 100, 50 & 25NTU are presented here. Since the chambers are fairly large in size compared to the diameter of the nozzle, the power input was calculated from the relationship

$$G = \sqrt{\frac{P}{\mu V}}$$

4.3 EFFECT OF BASIN SHAPE

Figure.3. shows the Effect of basin shape on turbidity removal

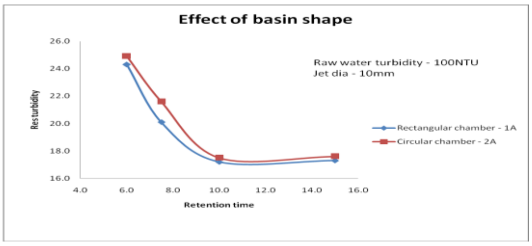

FIGURE.3. EFFECT OF BASIN SHAPE ON TURBIDITY REMOVAL

With the 8 mm diameter nozzle, the L/d ratio for the circular basin was 62.5 whereas in case of the rectangular basin it was 55.4. From the theory of free jets it is known that most of the kinetic energy of the jet gets dissipated within a distance of 40 to 45 times the diameter of the nozzle. Hence, it will not be unreasonable to assume that the energy loss in both the chambers is one and the same. It is interesting to observe that the performance of the rectangular basin is almost identical to that of the circular shaped basin, that is the shape of the flocculator is of no consequence.

A significant increase in the L/d ratio, as in case of the rectangular basin number 3 with circular opening, does help a bit to improve the turbidity removal efficiency. It can be noted that a rectangular basin should be marginally superior compared to the circular shape. This is in consonance with the measurements, where the efficiency of turbidity removal in the case of the rectangular basin is higher by 0.5%. In view of the fact that rectangular chamber are easy to construct and changing the length of the tank is also easy at a later time, a rectangular shaped basin has a distinct advantage over other shapes. Interestingly, the performance of the free jet flocculator is comparable to the actual performance, 69 to 74% turbidity removal efficiency, reported by Bhole (1993) and Armal (1997) for static flocculators and clariflocculators, respectively.

Location of outlet

Figure.4 shows that the Effect Of Outlet Location On Turbidity Removal

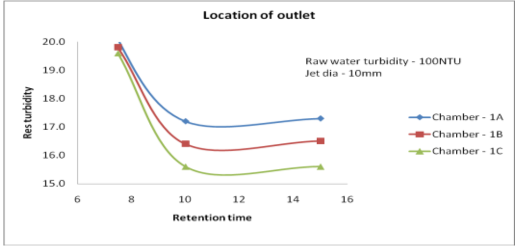

FIGURE.4 EFFECT OF OUTLET LOCATION ON TURBIDITY REMOVAL

The outflow section could be located at a convenient spot on the periphery of the chamber. The three alternatives experimented with are shown in Fig.. The experimental results, Table indicates that outlet 'C' performs superior to alternatives 'A' and 'B'. Further in all the cases, performance of a 12 mm diameter jet proved to be slightly better than 8, 10 and 15 mm diameter jets. Results pertaining to all basin alternatives are shown in. The location of the outlet plays a minor role in the overall efficiency of turbidity removal. This aspect can allow placement of the outlet at any convenient location as dictated by the prevailing conditions on-site.

Effect of Camp's no.

Figure.5 shows the effect of camp's no. On turbidity removal

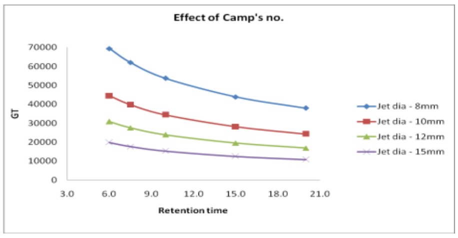

FIGURE.5 EFFECT OF CAMP'S NO. ON TURBIDITY REMOVAL

The value of G for the 12 mm jet corresponding to a retention time of 10 min works out to be $39.75s^{-1}$. This value is comparable to the optimal value of G equal to $42s^{-1}$ suggested by Andreu-Villegas and Letterman (1976). Even increasing the retention time to 15 and 20 min by lowering the jet velocity did not improve the performance as the large sized flocs were fragile. Thus, for a jet flocculator an optimal diameter exists when the retention time is specified. The same was found to be valid for other raw-water turbidities as well. The variation of GT value with respect to retention time for different jet sizes are shown in Fig.. The original Camp number, GT can be seen to vary over a wide range eventhough differences in the removal of turbidity were not remarkable. Hence, it is difficult to assign any particular value to GT for design purpose. The usage of G and GT parameters, though simple, cannot explain the actual performance of the flocculator vis-a`-vis the plan shape of the tank and the location of the outlet.

Residence time distribution

Figure.6 shows the Residence Time Distribution In A Square Tank

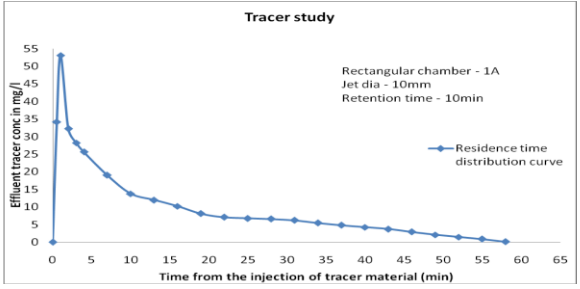

FIGURE.6 RESIDENCE TIME DISTRIBUTION IN A SQUARE TANK

A typical time distribution curve of the tracer for the case of a square tank corresponding to a detention time of 10minutes and for a jet diameter of 10mm is depicted in fig.. A material balance check was performed to ensure that the entire tracer material added in the tank was recovered. The errors were in the range of 1.5% to 4.5%.

Another graph as shown in fig. is plotted with cumulative concentration as a percentage and time on log scale. From this graph the dispersion index was calculated. The dispersion index so obtained then plotted against retention time for different basin shapes and for a jet diameter of 10mm as shown in fig.4.6.1. For an ideal plug flow DI=1, and for a completely mixed flow DI=21.9. From table, it can be seen that the DI values are nearly equal to the value of a well mixed flow whereas some are even higher. The higher values are indicative of the existence of flow short circuiting. For superior performance, the DI value should be as low as possible. It can be seen that for the same jet diameter and retention time, flow short circuiting in a rectangular basin is comparatively less than that of a circular basin. This factor again improves the efficacy of a rectangular basin.

Figure.7 shows the Residence Time Distribution In A Square Tank. Figure.8 shows the dispersion index variation in rectangular and circular tanks. Figure.9 shows the residence time ratio

The plot of log[1-F(t)] versus t/T, yields a straight line having a slope of loge/(1-m)(1-p). Further for F(t)=O, log 1-f(t) being zero, we get t/T = p(1-m). Thus, from the slope of the straight line and the value of t/T corresponding to F(t)=O, fraction of dead space (m) and plug flow (p) computed and the values so obtained are as follows.

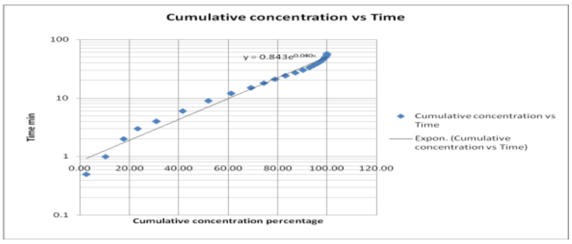

Figure.7 Residence Time Distribution In A Square Tank

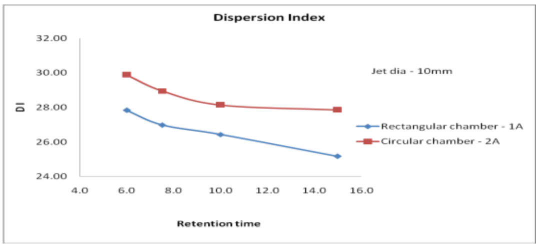

Figure.8 Dispersion Index Variation In Rectangular And Circular Tanks

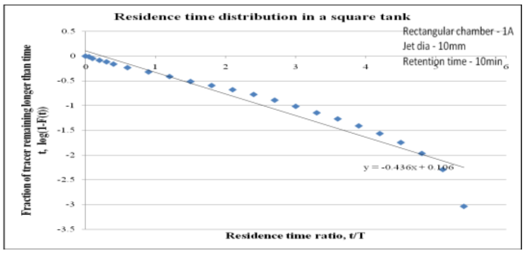

Figure.9 Residence Time Ratio

dead space = 3.47%
effective volume = 96.53%
plug flow = 19.62%
mixed flow = 90.38%

Out of many sizes and shapes of flocculation basin considered for carrying out tracer studies, results of a few are given in Table.2.

Dispersion Index

Based on the above results the proportion of dead space for all of them is quite small and is of the order of 3-5%. The implication is that site condition that demand specific position of the outlet can have the same turbidity removal efficiency. Dispersion no. and dispersion index of jet mixer too in the recommended range (0.3-0.7) for mechanical mixers. For all values of T ≥ 10min, mixed flow proportion nearly the same. For T = 10min, Di/uL is larger indicating better mixing of tracer in the flocculator.

Table.2 Tracer Studies & Results

Chamber no.	T in min	Plug flow%	Mixed flow %	Dead space %	D_i/uL	DI
1A	7.5	23.45	76.55	3.14	0.45	26.97
	10	19.62	80.38	3.47	0.59	26.58
	15	18.91	81.09	4.25	0.51	25.17
	20	19.52	80.48	5.63	0.47	25.10
2A	7.5	24.65	75.35	3.21	0.42	28.95
	10	20.15	79.85	3.35	0.55	28.14
	15	18.62	81.38	4.20	0.51	27.86

Single and multi jet nozzles

Figure10. shows the Effect of single and multi jet nozzles in turbidity removal. Figure.11 shows the effect of single and multi jet nozzles in flow pattern

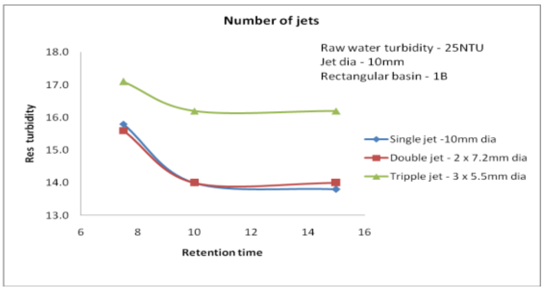

Figure10. Effect Of Single And Multi Jet Nozzles In Turbidity Removal

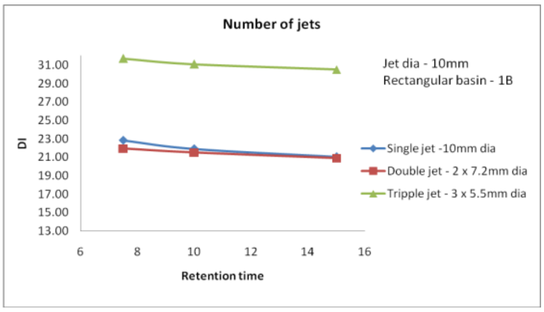

FIGURE.11 EFFECT OF SINGLE AND MULTI JET NOZZLES IN FLOW PATTERN

From the study it can be observed that the removal efficiency goes on decreasing as the raw water turbidity reduces. In the case of 100NTU turbid water the turbidity removal rate is as high as 84.9% but in the case of 25NTU turbid water it is only 48%. Multi jet nozzles have been tried to reduce the flow circuiting in flocculation basins. From the above it can be seen that the turbidity removal efficiency of double jet nozzles remained same as that of single jets. As the number of jets further increased which drastically reduces the removal efficiency. It is evident from study that the flow distribution in a double jet nozzle flocculator is superior to single jet flocculator. Since the turbidity removal rate remains the same and in the practical point of view, there is not much benefit in adopting multi jet nozzles.

VI. CONCLUSIONS

The outcome of the current experiments can be summarized as follows.

1. The single basin jet flocculator is a very simple, robust, low cost device which is capable of removing turbidity from the raw water in an efficient way. The efficiency of turbidity removal for raw water turbidity of 100 NTU was in the range of 79 to 85, which is as good as that of a flocculator fitted with mechanical stirrers.
2. The residual turbidity for raw water turbidity levels of 100, 50 & 25NTU was in the range of 13 to 21NTU. The outlet water with such a residual turbidity range can be directly applied over filter units for further treatment.
3. The retention time for a jet flocculator should be at least 10 min, a figure which is much less than the recommended value of 30 min duration for mechanical flocculators.
4. The length to diameter ratio, L/d should be larger than 36.
5. The plan-shape of the basin is not very critical in controlling the performance of the flocculator. For ease of construction and scope for future alteration, a rectangular flocculator is desirable.
6. The location of the outlet plays a minor role in the overall efficiency of turbidity removal. This aspect can allow placement of the outlet at any convenient location as dictated by the prevailing conditions on-site.
7. By adopting larger diameter nozzles the efficiency of turbidity removal can be enhanced.
8. The existing indices such as G, GT and MI, though useful for design purpose, are not able to explain the variations in the performance of the jet flocculator vis-a`-vis the shape, nozzle diameter, L/d ratio etc.
9. In adopting the jet flocculator for a new or an existing water treatment plant, the parameter G or GT (23,000 to 50,000) can be used in the design as a starting point. Other proposed indices can only help to refine the design and all the indices should be examined together before finalizing the dimensions and layout of the flocculation chamber.

An example is included in Appendix A as an illustration of the design principle of jet flocculators.

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