APPLICATION OF INCLINED TUBE SETTLERS IN URBAN WATER SUPPLY

by

Sow, Kim Leng

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Engineering.

Examination Committee:

Prof. N.C. Thanh (Chairman)
Dr. B.N. Lohani
Dr. S. Vigneswaran

Sow, Kim Leng

Nationality : Malaysia

Previous Degree : B.Sc. Engineering, University of Aberdeen, Aberdeen, Scotland.

Scholarship Donor : The King's (Royal Thai Government)

Asian Institute of Technology
Bangkok, Thailand
April, 1983

ACKNOWLEDGEMENTS

The author wishes to express his profound gratitude to Professor N.C. Thanh for his guidance, invaluable suggestions and friendly discussions throughout the course of this research.

Sincere thanks are extended to Dr. B.N. Lohani and Dr. S. Vigneswaran for serving as the committee members. Credits should also go to the Directors and the Deputy Directors of the Bang Khen Water Treatment Plant for providing such an excellent facility and friendly cooperation. Many thanks to the staff in the Plant for their understanding and cooperation during the course of experimentation.

Much appreciation is addressed to the staff of the Environmental Engineering Division for providing all assistance to make the experiment possible. Thanks also to my friends in the Division for their aids.

The author is extremely grateful to AIT and The King's (Royal Thai Government) Scholarship for providing the financial assistance during his stay in AIT.

Last but not least, this research is delicated to his parents for their endless encouragement and patience throughout the study.

ABSTRACT

A study of a pilot scale inclined tube settler was conducted at the Bang Khen Water Treatment Plant, Bangkok, Thailand, in an attempt to verify the applicability and the role that the tube settler can play in the modern water treatment plant. The experimental results concluded optimistically that the tube settler can provide comparable performance as that of the conventional sedimentation tank. In addition, it possesses the advantages of short detention time of only 14 minutes and that the construction costs of the tube settler is 3/4 that of the conventional sedimentation tank. As for the land requirement, tube settler needs only 1/4 the land necessary for the construction of sedimentation tank.

The performance of the tube settler was evaluated using natural flocculated water at various turbidity ranges and flow rates. Experimental results reviewed that addition of polyelectrolytes does not impart significant effect upon the settling efficiency. If 80% of removal efficiency is acceptable as the design criteria, then the overflow rates of 12.75 m^3/m^2d and 18.50 m^3/m^2d can be used for raw water turbidity of 25-37 NTU and 36-45 NTU, respectively. To cater for the stringent effluent quality of 5 NTU, overflow rate of 8.75 m^3/m^2d is satisfactory for raw water turbidities of 25-37 NTU if the system is working under optimum alum dose. For 'economic' alum dose, overflow rate of 8 m^3/m^2d can be used to satisfy the effluent requirement.

The present study also confirmed that column settling analysis can be used to provide the correlation for the scale-up of the pilot plant tube settler. For natural flocculated water, a safety factor of 2 can be used for tube settler design.

Plenum forms an important component of the tube settler system. Empirical formulae were developed in this research to take into account of the sludge scouring and the turbulent effect and at the same time to cater for the period needed for desludging.

LIST OF SYMBOLS

A_o	Cross sectional area of entrance
A_x	Cross sectional area of distance x
$B_o = B_x$	Longitudinal width of plenum
C	Unit adjustment constant
C_1	Adjusted integration constant
C'	Integration constant
d	Diameter
d_o	Floc size at entrance
d_x	Floc size at distance x
E	Efficiency
f	A frictional factor
g	Acceleration due to gravity
h_c	Settling column depth
h_o	Depth of plenum at entrance ($h_o = h_x = 0$)
$h_x = 0$	Depth of plenum at entrance
$h_x = L_p$	Depth of plenum at entrance $x = L_p$
$h_s, x = 0$	Depth of settled sludge at entrance
$h_s, x = L_p$	Depth of settled sludge at distance $x = L_p$
$H_x = 0$	Total plenum depth at entrance
$H_x = L_p$	Total plenum depth at distance $x = L_p$
K	A constant with magnitude close to S_g
L	Relative length
L_p	Total longitudinal length of plenum
n	A constant
Q_o	Flow at entrance section
Q_x	Flow at distance x
R	Removal efficiency (%)
R_e	Reynold's Number
S or S_c	Shape factor or critical shape factor
S_g	Specific gravity of the floc particle
t	Time at t
t_s	Settling time

LIST OF SYMBOLS (CONT'D)

U	Velocity in x direction
V_d	Displacement velocity
V_o	Overflow rate
V_s	Settling velocity
V_{px}	Velocity of particle in x direction
V_{py}	Velocity of particle in y direction
V_{sc}	Critical overflow rate
x	x coordinate
X_s	Distance across the plenum length
y	y coordinate

Greek Symbols

θ	Angle of inclination to horizontal

TABLE OF CONTENTS

TABLE OF CONTENTS (CONT'D)

I INTRODUCTION

1.1 General

The thirst of civilized man is unsatisfiable. The more sophisticated he becomes the thirstier he seems to be. In the so-called developing countries as little as 12 litres of fresh water sometimes suffices as the daily supply for each person, while in the developed countries, the daily demand in urban areas surpasses 150 to 200 litres per head. Yet this it only part of the story; as for man becomes more advanced he needs more and more water for commerce, industry, public institutions, power stations, and many other uses. Adding to this unremitting increase in demand, the ceaseless growth in the world's population and the yearn of achieving higher standard of living enable man to have a glimpse of the extent of the problem it presents, a problem that today seems to be happening in more and more areas around the world.

Apart from water supply, the quality of supplied water should be safe to drink, such demand imposes stress upon the engineers to provide water which is free from organisms and from chemical substances that may be hazardous to health. In addition, coolness, absence of turbidity, colour and disagreeable taste or smell are of prime concern.

In 1981, WHO estimated that approximately three out of five persons in the developing countries do not have access to safe drinking-water (see Table 1.1). For the urban areas, about 75% of the population having some form of water supply through house connections or standpipes while only 29% have equivalent water supply in rural areas.

TABLE 1.1

Estimated Service Coverage for Drinking-Water Supply in Developing Countries, 1970-1980[1]

Year	1970		1975		1980	
	Population Served (in million)	Percentage of Total Population	Population Served (in million)	Percentage of Total Population	Population Served (in million)	Percentage of Total Population
Urban	316	67	450	77	526	75
Rural	182	14	313	22	469	29
Total	498	29	763	38	995	43

[1]WHO (1981) (United Nations Document A/35/150)
Figures do not include the People's Republic of China.

To combat the above situations, the decade from 1981 to 1990 has been designated an International Drinking Water Supply and Sanitation Decade. It represents a concerted effort by the entire international community to extend and improve water supply and sanitation worldwide. The decade's targets were first formulated at the 1976 United Nations Conference on Human Settlements in Vancouver. There, a resolution was passed urging the adoption of programs for urban and rural areas that would lead "if possible" to safe water supply and hygienic waste disposal by 1990 for all human settlements.

1.2 Sedimentation

In tropical regions, high turbidity is one of the main characteristics of the surface water. Pretreatment is therefore often necessary for water treatment plants using surface sources taken from the streams. Chemical coagulation followed by flocculation and sedimentation is normally the process used in the conventional filtration plants.

Sedimentation is one of the most widely used unit operation for removal of turbidity and to concentrate solids in many diversified fields. It is the most commonly used process in the field of water and sewage treatment. The investments for settling in this aspect are probably about one third of the total capital investment for treatment. Despite the importance of the process, its basic design criteria have remained without significant change for well over 50 years.

In late 1960's tube settler was developed and has now been considered as an accepted process for water treatment in most parts of the world. It provides a breakthrough in the old practice and a newtool for increasing the efficiency of sedimentation and reducing the cost of settling. In 1904, HAZEN undertook the first realistic approach of the tube settling system which was later explored extensively by CAMP in 1946. These units have small size tubes of various shapes and operate at detention times of not more than 15 minutes (YAO, 1973). The system accomplishes almost ideal condition of settling i.e. laminar flow conditions, shallow depth, absence of thermal currents and elimination of short circuiting.

To-day, two basic shallow depth settling systems are commercially available, there are the essentially horizontal tube settler (with 5-degree of inclination to the horizontal) and the steeply inclined tube settler (with angle of inclination to the horizontal in the range of 45-degree to 60-degree). The former tube system installed prior to the filter units and the cleaning is accomplished by backwash water from the filters. For steeply inclined tube settler, the sludge is removed by mean of gravity.

1.3 Objectives of the Research

Tube-settlers are compact and can provide the benefits of significant cost savings in construction and land costs. They can also be used for upgrading an existing overloaded conventional sedimentation tank and still provide comparable or better settling efficiencies normally obtained in conventional settling tanks. The various other advantages offered by the tube settler make it essential to develop design criteria for the clarification of tropical turbid waters.

In the developing countries where resources are scarce, therefore seeking toward appropriate technology which could lead to a cost-effective system for water treatment is of prime importance. In Asian Institute of Technology, many research studies were conducted in the past ten years to investigate the effects of various factors and parameters which affect the performance of the tube settler efficiency. Tube length, tube size, flow rate, overflow rate, raw water turbidity, angle of inclination and shapes of tubes were among the factors and parameters considered in the researches (see Table 1.2).

The aims of this study are devoted mainly to the application of tube settler design based upon the findings from AMIN (1974), BINH (1975), LIENGCHARERNSIT (1975), VASANADELOKLERT (1978), CHEN (1979) and PANNEERSELVAM (1982). The other principal objectives of the present research are as follows:

(i) To evaluate the role of the tube settler in the water treatment systems and to investigate the performance of the tube settler at various overflow rates, flow velocities and influent raw water turbidities.

(ii) To conduct an in-depth study of the plenum design and to arrive at empirical formulae which give the optimum design of the plenum.

(iii) To investigate the use of settling column and jar test techniques to provide a correlation for the scale-up of the plant size tube settler.

(iv) To determine the effect of settling depths upon the correlation factors obtained from objective (iii).

(v) To look into the effect of residual current upon the performance of the settling column.

(iv) To evaluate the creditability of the tube settler by estimating and comparing the costs of the tube settler with the conventional sedimentation tank.

1.4 Scope of Study

The research was carried out on pilot scale tube settler inclined at 60 degrees to the horizontal with relative length L=18. The experiment was conducted in the Bang Khen Water Treatment Plant and it consisted of three phases:

Phase 1: The effect of the operational variables upon the efficiency of turbidity removal was studied. The operational variables investigated were: overflow rate (2.0 to 30 m^3/m^2-d);

TABLE 1-2

Past Researches on Inclined Tube Settler Undertaken at The Asian Institute of Technology, Bangkok, Thailand.

Author	Description of Research	Conclusions of research
AMIN (1974)	Aim: To evaluate the performance of horizontal tube settler; Source: A.I.T. klong's water; Turbidity: 30 - 95 NTU.	Effective in the turbidity removal and continuous sludge removal is achieved. Tube settler gave comparable efficiency when compared to upflow contact basin but it has shorter detention time.
LIENG-CHARE-RNSIT (1975)	Aim: Application of bamboo and corrugated asbestos as tube settlers; Source: A.I.T. klong's water; Turbidity: 100 - 140 NTU.	80 % efficiency achieved with length of 120 cm and Vsc of 8 m^3/m^2 d. Angle of inclination of 60 deg. was the best. Corrugated asbestos tube settler gave better performance than bamboo settler but it cost more.
VASANA-DILOKL-ERT (1978)	Aim: Practical application of bamboo tube settler in water treatment plant; Source: Chao Phya River; Turbidity: 60 - 72 NTU.	Removal efficiency of 93.8% was achieved with tube length 120cm, dia. 6.3 cm, Vsc of 2.5 m^3/m^2 d at θ=45 deg.. Cost of bamboo settler was 1/2 the cost of settling tank and land used was 1/3 of the sedimentation basin.
CHEN (1979)	Aim: Developed design criteria for inclined tube settler and plenum; Source: Synthetic water; Turbidity: 20 - 100 NTU.	Relative length of 14.9 was the economical value for square tube. Mathematical formulations were developed for the efficiency of the tube system and the plenum design was investigated.
PANNE-ERSEL-VAM (1982)	Aim: To study the performance of inclined tube settler, relative length of 18 and θ=60 degrees; Source: Synthetic water; Turbidity: 50 - 180 NTU.	Recommended overflow rate and flow velocity of 4 m^3/m^2 d and 4 m^3/m^2 h respectively. Column settling can provide scale-up for the pilot scale tube settler system. A safety factor of 2 was applicable. Plenum design was also investigated.

influent raw turbidity (25 NTU to 45 NTU); flow velocities ($2\ m^3/m^2$-h to $8\ m^3/m^2$-h).

Phase 2: Experiment was carried out first to determine the desirable plenum bundle (of depth 0.2 m; 0.3 m; 0.6 m). For the specific plenum bundle, the depths of the accumulated sludge at the different points across the plenum length (X1 = 0.0 cm; X2 = 8.0 cm; X3 = 16.0 cm; X4 = 24.0 cm and X5 = 32.0 cm) were measured for different flow velocities.

Phase 3: In the column settling analysis, single level sampling was used. Percentage of the turbidity removal at different settling column depths (10 cm; 30 cm; 50 cm; 70 cm and 100 cm) and at different time intervals were recorded. The effect of residual current upon the performance was also determined by using the conventional jar test technique and the revised jar test technique using square tank.

II LITERATURE REVIEW

2.1 Historical Development of the Tube Settler

HAZEN (1904) recognised that the proportion of sediment removed in a settling basin is primary a function of the surface area of the basin and it is independent of the detention time. He pointed out that doubling the surface area by inserting one horizontal tray would double the capacity of the basin.

BRAHAM et al. (1956) reported one of the first attempts on practical application of tray-settling principle which was patented in 1915. Several shallow settling compartments were formed by a series of conical, circular trays placed one above the other. The solids collected on each tray were scraped to a centrally located sludge collection tube which then transports the sludge to the bottom of the tank.

FREI (1941) inserted three circular, steel, radial-flow trays to an existing primary sewage clarifier. He reported the efficiency of the suspended solids removal increased from 41 to 61 per cent even though the flow through the tank was tripled following the addition of the trays.

CAMP (1946) assumed a uniform velocity profile of the tank and thus the particles followed a straight trajectory in passing through the tank. He then presented a design for a settling basin with horizontal trays spaced at 12.24 cm (6 in) which he left the minimum distance for mechanical sludge removal. The basin had a detention time of 10.8 min, a velocity of 168 m^3/m^2-h, and overflow rate of 27 m^3/m^2-d. Outlet orifices were used to distribute the flow over the width of the trays.

SCHMITT and VOIGT (1949) mentioned the use of a two-storey settling basin in a water treatment plant. The trays were arranged in series and spaced at 4.75 m (15 ft) and were cleaned by draining and hand-hosing. DRESSER (1951) reported a similar use of series of trays in the Cambridge, Mass., water treatment plant. The trays were spaced at 1.524 cm (5 ft) and sludge removed by gravity with nozzles mounted at the end.

All attempts in 1940's and 1950's at the applications of shallow depth sedimentation met with limited success due to two major problems:

(1) the difficulties encountered in proper distribution of flow to a large number of trays,

(2) sludge removed from closely spaced trays.

To maintain proper hydraulic conditions for efficient sediments, FISCHERSTROM (1955) felt that a Reynolds number of 500 (limit of laminar flow at 32°F) in the settling would be most beneficial to the settling process. He pointed out that the Reynolds number could be lower to the laminar flow range by increasing the wetted perimeter, or inserting longitudinal, horizontal or vertical baffles in the basin.

HAZEN and CULP (1967) reported that longitudinal flow through the tubes with diameter of few inches offered theoretically optimum hydraulic conditions for sedimentation. Such tubes often provide very low Reynolds number. This show that even with largest tube and highest flow rate the Reynolds number was only 96 which is far below the upper limit of laminar flow of 500.

CULP et al. (1968) described the two basic tube settler systems, namely the essentially horizontal tube settler and the steeply inclined tube settler, where both of them are now commercially available. He concluded that for tube inclined at an angle of 60 degrees to the horizontal, continuous sludge removal is possible.

HANSEN et al. (1969) observed that if the tube is inclined at an angle of greater than 45 degrees, then the sediments accumulated on the surface of the tube begins to move down after reaching a certain depth. This countercurrent flow of the solids aids in the agglomeration of particles into larger, heaver flocs which are able to settle against the upwardly flowing liquid.

YAO (1970) developed a mathematical model for the tube settlers with the assumptions that the flow is laminar and one-dimensional and that the suspended particles are discrete. He formulated a formula describing the relationships between the shape of the tube, relative length and the angle of inclination upon the settling efficiency.

YAO (1973), based on his previous model and coordinates system, arrived at an important equation of overflow rate against the shape factor, relative length and the angle of inclination. He also pointed out that the higher the raw water turbidity, the higher the removal efficiency for all overflow rates.

AMIN (1974) investigated the performance of the essentially horizontal tube settler and the steeply inclined tube settler. He found that the steeply inclined tube settler performs beter than the essentially horizontal tube settler in terms of higher flow rate (10 m^3/m^2-h compared with 2.45 m^3/m^2-h). shorter detention time (5.5 min compared with 20 min), and higher efficiency (80% compared with 60-70%).

CHEN (1979) developed a model based upon the hydraulic conditions in the tube and eventually arrived at a formular which is similar to the equation for overflow rate developed by YAO in 1973. From CHEN model, he recommended that the relative length of 14.9 and the flow rate should keep below 10.7 m^3/m^2-h.

2.2 Parameters Affecting Tube-Settler Performance

YAO (1970) based on his model derived an expression for the critical particle fall velocity for a given high rate settling system:

$$V_{sc}/V_o = S_c/(\text{Sin}\theta + L\text{Cos}\theta) \qquad (2.1)$$

where L is the relative length,

V_{sc} is the overflow rate,

V_o is the average flow velocity,

S_c is the shape factor,

θ is the angle of inclination

From this expression, he concluded that tube shape has an effect upon the value of S_c which in turn affects the efficiency of the tube settler. For the circular tube, parallel plates, square conduits and shallow open trays, he calculated the value of S_c for each case to be 4/3, 1, 11/8, and 1, respectively. Therefore, in chosing the tube shape, the following criteria should satisfy:

(1) the tube height should be as short as possible to minimize the settling distance,

(2) uniform settling distance is desirable so that most particles have the same settling time,

(3) tube shape should permit nesting so that there is no wasted space between tubes in the unit,

(4) as far as possible, the shape should promote sludge compaction and flow.

BEACH (1972) concluded that chevron shape is the best design fulfilling all the above conditions and for 1 in chevron configuration, it has the higher perimeter of any common shape of the same area.

CULP et al. (1968) investigated the influence of tube inclination on the settler performance. They concluded that the efficiency increases as the angle of inclination increases to 35-45 degrees and then begins to decrease as the angle of inclination increases further. But as the angle of inclination increases beyond 45 degrees, promotion of self desludging by gravity becomes significant. 1973, YAO stated that it is necessary to sacrify the system efficiency so as to achieve self cleaning action at an angle of inclination of 60 degrees.

In 1975, a different situation was encountered by BINH. For velocities of 12.5 cm/min and 16.7 cm/min, the tube settler inclined at 40 degrees gave slightly better performance than the one inclined at 60 degrees while the third inclined at 50 degrees gave the lowest efficiency. In addition, at higher flow velocity (20.8 cm/min), the removal efficiency was not affected significantly by the variation of angle of inclination, which agree well with the remark made by YAO in 1973.

Raw water turbidity imparts a significant effect upon the settling performance of the tube settler. YAO (1973) and PANNEERSELVAM (1982), both claimed that the higher the raw water turbidity, the better the removal efficiency for all flow rates. The reasons for such improvement could be due to better flocculation before settling at higher turbidity.

Tube diameter can also plays an important role in the tube settler system. As the tube diameter increases, the turbidity removal efficiency decreases and the effect is much more significant at higher flow rate than that at lower flow rate. Small diameter offer lower Reynolds number thus promote laminar flow which facilitates better settling performance.

Polyelectrolyte addition has positive and negative effect on the settling performance and its consequence depends very much upon the characteristics of raw water. HAZEN et al. (1967) concluded that addition of 0.2 mg/ℓ to 0.5 mg/ℓ of polyelectrolyte could achieve better settling performance while AMIN (1974) reported that addition of polyelectrolyte does not enhance settling.

HANSEN (1967) and others reported that the turbidity removal efficiency decreases as the overflow rate increases. In 1973, YAO concluded that if the overflow rate criteria for the conventional sedimentation tank design is used for designing high rate settlers, the later should provide better performance within the practical range of overflow rate. He also stated that if 80% removal efficiency is acceptable, then overflow rate of 61 m^3/m^2-d can be used. WILLIS (1978) specified the maximum overflow rate value has varied from 3.6 m^3/m^2-d to 16 m^3/m^2-d based upon the tube end area. AMIN (1974) recommended that the overflow rate should not exceed 13 m^3/m^2-d while PANNEERSELVAM (1982) concluded that the overflow rate of 4 m^3/m^2-d is the best. The above variation of overflow rate could be due to the difference in tube settler design, size, different raw water used, and different experimental conditions.

2.3 Practical Applications of Tube Settlers

2.3.1 Primary Treatment of Sewage Effluent

SLECHTA and CONLEY conducted a plant scale installation of settling tubes in a primary clarifier at Philomath, Ore. In 1968 and concluded that settling tubes can be used to improve the quality and possible increase the capacities of those installations where a serious carry-over of solids exists. In those installations where a good primary effluent is being obtained, an increased in the capacity is possible provided the hydraulic limitations of the basin are not exceeded. They found that for the same solid removal efficiency, a three-fold increase in the flow-rate is possible for tubes loaded at 6-10 m^3/m^2-h based on the end area of the tubes. They also noted that no improvement in the primary effluent quality can be achieved through the use of settling tubes alone in a basin already providing essentially complete settleable solids removal and 40-60 per cent suspended solids removal. During the first few months of operation, no maintenance problems have developed but after 6 months of operation, a mat of 0.1 m thick had formed on the top of the tube and floating septic sludge was observed. The problem was overcome by installing a submerged water jet and agitating the module on weekly basis.

2.3.2 Upgrading Humus Tank

In 1975, Water Research Centre carried out a full-scale module of slopping tubes installed in one of two humus tanks in a small works serving a village in the United Kingdom. Results indicated that the solid removal efficiency depends upon the nature of the influent solids and the upward-flow velocity calculated from the total plan area of the inclined plates. For influent suspended solids concentration of 100 mg/ℓ (in Winter), the rate of flow can be increased to three times in the modified tank for the same effluent quality. For influent suspended solids concentration of 150 mg/ℓ (late Spring), the flow-rate could be increased to only 60 percent, while for 50 mg/ℓ (Summer) of influent suspended solids, no appearent benifit was gained from installing the module. In the course of the experimentation, no denitrification occured and the module was cleaned every two weeks to prevent the growth of slimes.

2.3.3 Secondary Treatment of Sewage Effluent

Inclined tubes had been installed in the final settling tanks at a number of full-scale activated sludge plants in U.S.A. The first field installation was made at the Wickam Sewage Treatment Plant, Pennyslvania (Fig. 2.1). Initial results were promising but experience over a long period showed that there was periodic discharged of solids and fouling of module. Fouling can be prevented by provision of submerged water jets, module agitation or air scrubber. It was recommended that the loading should not exceed 3 m^3/m^2-h based on the tube end area and provision for removal of floating sludge must be ensured.

DICK (1970) pointed out that the final tank in the activated sludge process has a thickening role as well as a clarification role, and there is little advantage in upgrading such a tank if increase in the clarification capacity of a settling tank accomplished at the expense of thickening. This implies added cost of handling larger volumes of more dilute sludge or provision of separate sludge thickeners.

In Sweden, three major works were installed with self-contained modules of sloping plates designed to achieve a rapid return of sludge to the aeration tanks. Many problems were encountered such as bad distribution of suspension under the tube and rapid growth of algae during Summer time.

Tubes have also been used for secondary clarification in trickling filter plant, for example in the Philomath, Oregon Sewage Treatment Plant. Prior to the tube installation, the secondary clarifier effluent contained 60 mg/ℓ to 80 mg/ℓ of suspended solids but after the installation, the effluent quality has been excellent with suspended solids routinely less than 20 mg/ℓ at an average daily flow of 0.7 mgd. Another advantage as in the case of activated sludge plant, the capacity of an existing trickling filter plant secondary clarifier can be readily increased by installing tube modules over all or only a portion of the basin. No operational or maintenance problems have developed in the several months of operation.

2.3.4 Tertiary Treatment of Sewage Effluent

CULP et al. (1969) showed that the general system as shown in Figure 2.2 can be employed for the phosphate removal from the secondary effluent by chemical coagulation. A report issued by FWPCA on Shagawa Lake Project indicated that the secondary effluent phosphorus concentration can be reduced from 5-6 mg/ℓ to 0.3-0.7 mg/ℓ. In another instance, MERCER reported the tube clarifier mixed media filter package plant could reduced the secondary effluent turbidity from 10-12 to 0.3-0.7 (turbidity unit) and the phosphates from 26-28.5 mg/ℓ to less than 0.5 mg/ℓ. Alum addition is 240 mg/ℓ.

From SWEDEN successful used of inclined plates modules for the separation of aluminium floc formed in the treatment of the secondary effluent, has been achieved. Loadings as high as 30 m^3/m^2-h were reported.

Another tertiary system designed for BOD and suspended solids removal utilizing the tube clarifier is illustrated in Fig. 2.3. This system is designed to polish the occasional discharge of high suspended solids concentration from the secondary plant. Direct application of these secondary effluent to the filter would result in expensive short filter run, thus the purpose of the tube clarifier is to provide supplement solids separation so that the filter may continue to operate efficiently even during severe upset of secondary plant. Data published show that such system continuous to operate efficiently even with secondary effluent suspended solids concentration as high as 2000 mg/ℓ.

BINH (1975) reported that the inclined tube settler and the anthracite sand filter system can generally removed all aluminium resulted from the utilization of alum during the flocculation process.

VAN VLIET (1977) described the series of full scale experiments in which both inclined plate and tube module were used to uprate the conventional circular raked primary clarifiers of high lime clarification process. It was reported that the removal efficiency of both modules were comparable and a 60 percent turbidity removal was general attained within the modules.

2.3.5 Raw Water Clarification

The conventional plant at Buffalo Pond Plant, Saskatchewan was faced with the requirement of additional treatment capacity, thus the existing rapid sand filters were converted to mixed media beds and operate at higher filtration rates while steeply inclined tube settlers were used to cater for the increase in settling capacity. For 6 months of operation, the tube installation has operated at over 2.5 times designed rate of the parallel conventional units, while producing an average effluent of 0.5 unit. The installation of tubes in the conventional units permits a more than doubling of the clarifier capacity.

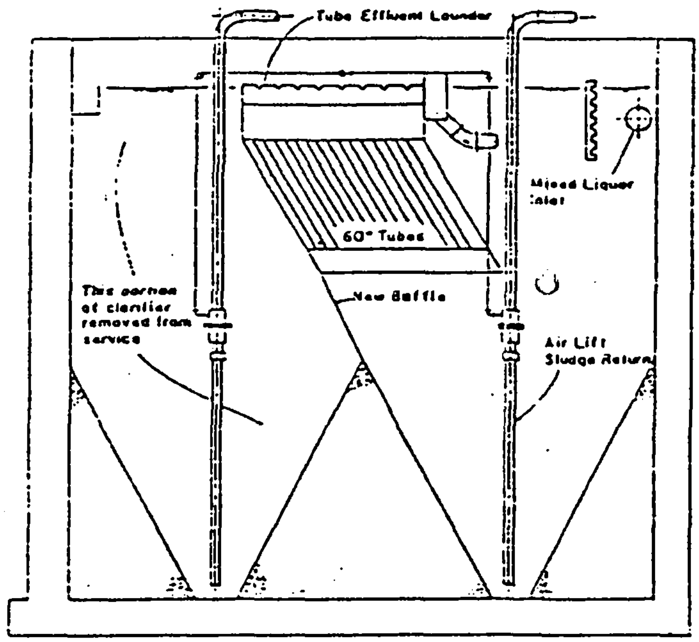


Fig. 2.1 - Installation of Steeply Inclined Tubes at the Wickam, Pennsylvania Sewage Treatment Plant.

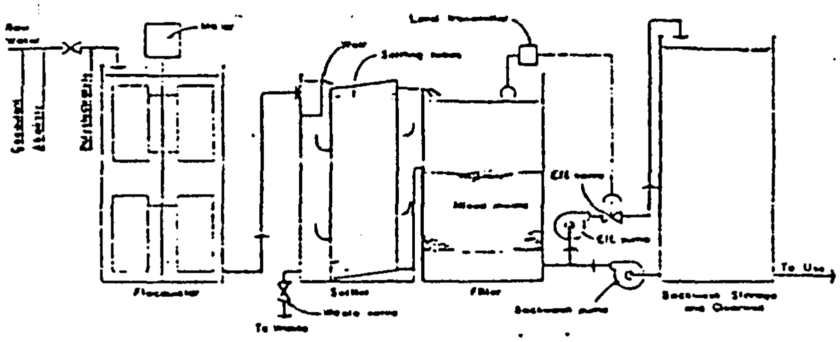


Fig. 2.2 - Flow Schematic, Basic System Employing Essentially Horizontal Tubes.

Another example of increasing the capacity of water treatment plant by utilizing tube clarifier and mixed media is the Georgia-Pacific's Pulp and Paper Mill at Crosselt, Arkansas U.S.A. It was reported that by installing angle tube modules over only a portion of the clarifier surface, the capacity was increased from 56,775 m^3/d to 170,325 m^3/d. From the test conducted, it reviews that for overflow rate of 4 m^3/m^2-h effective clarification observed even under cold water conditions.

The flow diagram as shown in Figure 2.3 has also been applied in many water treatment plants in U.S.A. with capacity varies from 0.0757 m^3/min to 7.57 m^3/min. For example at Emporia, Virginia, for raw water turbidity of 20 standard units, a effluent quality of 3 units can be achieved using alum concentration of 35 mg/ℓ and operate at overflow rate of 193 m^3/m^2-d with corresponding detention time of 10 minutes. Another plant located at Louisville, Mississippi with plant capacity of 7.57 m^3/min can provide an effluent quality of approximately 2 units using the same system as described above.

2.3.6 Other Applications

One of the most interesting applications now being evaluated is the use of steeply inclined tube directly in the aeration basins of an activated sludge plant. With proper baffling, it appears possible to achieve activated sludge solids separation and return without a secondary clarifier structure, therefore the economic implications in secondary plant construction are indeed significant.

2.4 Column Settling

In the world of limited resources, seeking toward economical techniques to predict plant scale performance or to derive design criteria for plant scale processes is of utmost importance.

YAO (1979), using column settling to predict the design overflow rate of the tube settler system. He reported that a safety factor of 2 was needed for uncoagulated synthetic water and natural unflocculated raw water. Table 2.1 shows the turbidity range involved and the experimental conditions.

PANNEERSELVAM (1982) concluded that for coagulated synthetic water of turbidity greater than 180 NTU, then the results obtained from the column settling tests can be used directly for designing the tube settler. For turbidity of 120 NTU and 80 NTU or less, a safety factor of 1.4 and 2 were respectively observed.

HUDSON (1981) claimed that the revised standard procedure of using square jar test (see Fig. 2.6) can be used to established the design overflow rate for tube settler system of plant size.

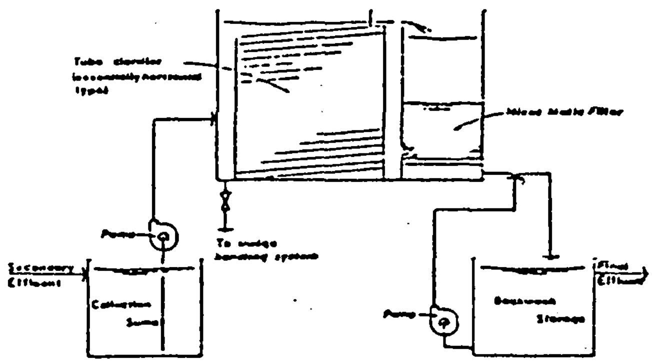


Fig. 2.3 - Schematic of Effluent Polishing System for BOD and Suspended Solids Removal.

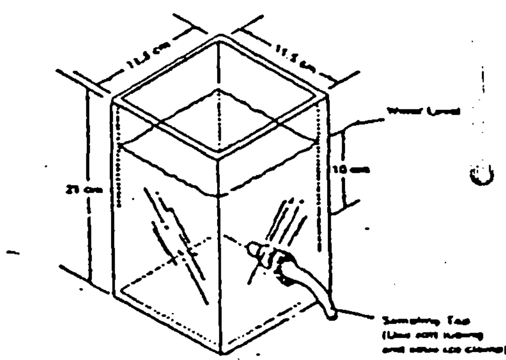


Fig. 2.4 - Revised Standard Jar Test (Hudson, 1981)

TABLE 2-1

Design Safety Factor for Overflow Rate Provided by Column Settling to the Tube settler System

Author	Nature of Water	Raw Water Turbidity (NTU)	Depth (cm)	Safety Facto
YAO (1979)	Natural Raw Water	100 - 280 (May-Sept)	78	2.0
		14 - 70 (Sept-Nov)	78	2.0
	Uncoagulated Synthetic Raw Water	100 - 280	78	2.0
PANNEER-SELVAM (1982)	Synthetic Flocculated Water	160 120 80	106 106 106	1.0 1.4 2.0

III SOME THEORETICAL CONSIDERATIONS ABOUT TUBE SETTLERS, COLUMN SETTLING AND PLENUM DESIGN

3.1 High Rate Sedimentation

High rate sedimentation is the use of shallow gravitational settlers with detention period of not more than 15 minutes to achieve comparable or even better settling efficiencies normally attained in the conventional sedimentation tanks having detention time of usually more than 2 hours.

The above idea was originally suggested by HAZEN (1904) who claimed that the removal is a function of the overflow rate and for a given discharge, it is independent of the detention time. CAMP explored the above concept extensively in 1946.

YAO (1970) conducted a theoretical research on high rate tube settlers of various shapes and arrived at a design equation based on the parameter "overflow rate", which is widely used in water and wastewater treatment process design.

He assumed that the flow is laminar and one dimensional and the suspended particles are discrete which do not aggregate. Ignoring the initial effect, the velocity components of the particles on the x and y directions based on the coordinates system as shown in Fig. 3.1 are:

$$\frac{dx}{dt} = Vpx = U - Vs \times \sin\theta \qquad (3.1)$$

$$\frac{dy}{dt} = Vpy = -Vs \times \cos\theta \qquad (3.2)$$

Combining equations (3.1), and (3.2)

$$\frac{dy}{dx} = -\frac{Vs \times \cos\theta}{U - Vs \times \sin\theta} \qquad (3.3)$$

Integrating equation (3.3),

$$\int U \cdot dy - Vs \cdot y \cdot \sin\theta + Vs \times \cos\theta = C' \qquad (3.4)$$

where

C' is the integral constant

Dividing equation (3.4) with Vo, the average flow velocity, and d, the depth of the flow measured normal to the direction of flow.

$$\int \frac{U}{Vo} \cdot dy - \frac{Vs}{Vo} \cdot Y \cdot \sin\theta + \frac{Vs}{Vo} \cdot X \cdot \cos\theta = C1 \qquad (3.5)$$

Where Cl is the adjusted integration constant, $Y = y/d$ and $X = x/d$ and equation (3.5) is the general equation of a particle trajectory in the given high rate settling system.

Each particle follows its own trajectory inside the tube settler (Fig. 3.2). F1, F2, F3, indicate the trajectories of particles removed by the settler because all three trajectories end at the invert of the settler. The trajectory, F1, represents a limiting case. All particles with the same Vs of the particle following this trajectory would be completely removed by the tube settler. This particular Vs is defined as the critical settling velocity, Vsc.

For the limiting trajectory with Vs = Vsc, there are two boundary conditions,

$$X = L; \quad Y = 0 \tag{3.6}$$

$$X = 0; \quad Y = L \tag{3.7}$$

in which $L = l/d$, the relative length; and l = the length of the settler. Therefore by substituting equations (3.6), (3.7) into (3.5),

$$C1 = \frac{Vsc}{Vo} \cdot L \cdot \cos\theta$$

Since the flow velocity vanishes at the settler wall (Y = 0), there results:

$$\left(\int \frac{U}{Vo} \cdot dy\right)_{y=o} = 0 \tag{3.8}$$

Substituting Cl and the second boundary condition, equation (3.7), into equation (3.5), the following general equation is obtained:

$$\frac{Vsc}{Vo} \cdot (\sin\theta + L \cdot \cos\theta) = Sc \tag{3.9}$$

$$Sc = \left(\int \frac{U}{Vo} \cdot dy\right)_{y=1} \tag{3.10}$$

in which Sc is a factor with its magnitude depending on the shape of the tube. The values of Sc for circular, parallel plate, square, and shallow open tray stellers are respectively 4/3, 1, 11/8, 1. For overflow rate, it can easily be seen that is exactly the same as the critical settling velocity, then,

Vsc

$$\text{Overflow rate} = C \cdot Sc \cdot \frac{Vo}{\sin\theta + L \cdot \cos\theta} \tag{3.11}$$

where C is a unit adjustment constant. For Vo(cm/min) and overflow rate (m^3/m^2-d), then C = 14.4.

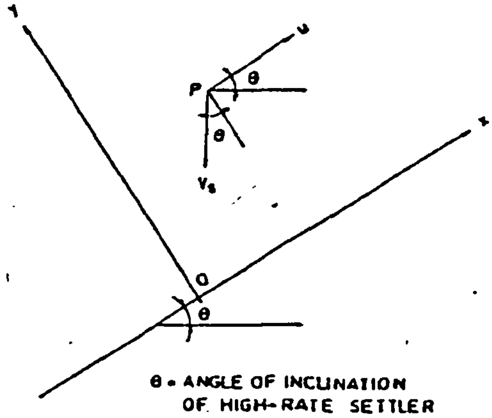


Fig. 3.1 - Coordinate System for Theoretical Study

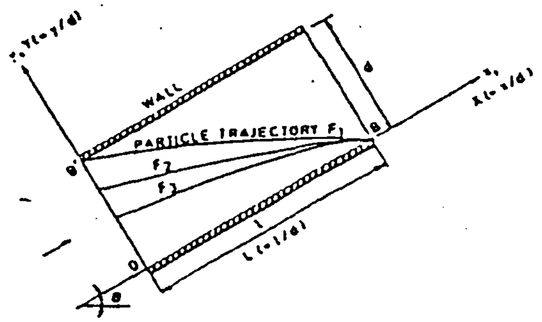


Fig. 3.2 - Sketch of Particle Trajectories in High-Rate Settler.

3.2 Column Settling

The clarification of dilute suspensions of flocculating particles is not only a function of settling properties of the particles but also of the flocculating characteristics of the suspension. During sedimentation, coalescence or flocculatin occurs, thus the mass of the particle increases and it settles faster. The extent to which flocculation occurs is dependent on the opportunity for contact, which varies with the overflow rate, the depth of the basin, the velocity gradients in the system, the concentration of the particles and the range of the particle sizes (RICH 1973; BARNES 1978; and TCHOBANOGLOUS 1979).

Since 1940's, overflow rate has been extensively used as a parameter for the design of the conventional settling tank. Besides, overflow rate can easily be obtained from the batch process of column settling tests and could be used to predict the performance of the conventional settling tank operated on a continuous basis. For these reasons, this study proposed to adopt overflow rate as the key design parameter to predict the performance of the tube settling system. For column settling, the overflow rate can easily be calculated as follows:

If hc(cm) is the distance between the water level and the sampling port and ts is the settling time (h), then the overflow rate,

$$Vs = hc/ts \text{ (cm/h)}$$

$$Vs = 0.24 \times hc/ts \text{ (m/d)} \qquad (3.12)$$

TCHOBANOGLOUS (1979) and RICH (1973) stressed upon the influence of depth on the clarification process, the higher the settling depth (i.e. larger the detention time), the better the efficiency of removal for certain overflow rates. HUDSON (1981) pointed out the important of controlling the depth of sampling such that the settled water quality data have much relation to reality. Therefore, it is the aim of this study also to verify the applicability of column settling and jar test to provide a scale-up correlation with the plant scale tube settler for natural flocculated water and at the same time to investigate the effect of depth upon the design safety factor.

3.3 Plenum Design

Plenum forms one of the important components of the tube settler system and its design is of considerable importance. In proper design of the plenum will severely affect the removal efficiency of the tube settler. If the plenum depth is too shallow, and if the horizontal velocity is high, then scouring of the settled sludge and turbulent condition will occur.

In 1968, FAIR et al. arrived at the following equation for scouring velocity:

$$Vd = \{(8K/f)\cdot g\cdot(Sg - 1)\}^{\frac{1}{2}} \cdot d^{\frac{1}{2}} \qquad (3.13)$$

where Vd = displacement velocity

f = a frictional factor

K = a constant with a magnitude close to S

g = the gravitational constant

Sg = the specific gravity of the floc particle

d = the diameter of the floc

CHEN (1979) assumed that K, f, g, Sc are approximately constant and $Qx = (Lp - x)Qo/Lp$.

$$\frac{Ax}{Ao} = \frac{(Lp - x)}{Lp} \cdot \left(\frac{do}{dx}\right)^{\frac{1}{2}} \qquad (3.14)$$

where Qo = the treated water flowing through entrance section

Qx = the treated water flowing through a section at a distance x

Lp = the total longitudinal length of plenum

Ao = cross sectional area at entrance

Ax = cross sectional area at a distance x

do = average floc size at entrance

dx = average floc size at a distance x

Fig. 3.3 shows the graphical representation of the plenum. CHEN also pointed out that the floc particle size varies in each section such that

$$dx = do \cdot \left(1 - \frac{x}{Lp}\right)^{n} \qquad (3.15)$$

Substituting equation (3.15) into (3.14), thus

$$\frac{hx}{ho} = \left(1 - \frac{x}{Lp}\right)^{1-n/2} \qquad (3.16)$$

If the plenum is rectangular, then the width of the plenum at entrance is equal to the width of plenum at any distance x from the entrance, i.e. $Bo = Bx$,

$$\frac{hx}{ho} = \left(1 - \frac{x}{Lp}\right)^{1-n/2} \qquad (3.17)$$

where

Bo = width of plenum at entrance

Bx = width of plenum at a distance x from the entrance

hx = depth of plenum at a distance x from the entrance

ho = depth of plenum at entrance

n = a constant

For practical operation, CHEN recommended that ho should be maintained equal to Co·Qo in which Co = 3.1 s/m^2 and Q is in terms of m^3 and thus the unit of hx will be in meter.

Let hs, x = 0 be the sludge depth at the entrance and hs, x = Lp, the sludge depth at a distance x = Lp from the entrance, then

$$Hx = 0 \text{ (cm)} = hx = 0 + hs,\ x = 0 \quad (3.18)$$

$$HX = Lp \text{ (cm)} = hx = Lp + hs,\ x = Lp \quad (3.19)$$

where

Ho = total minimum depth at entrance

Hx = total minimum depth at a distance x from the entrance

hx = o = ho

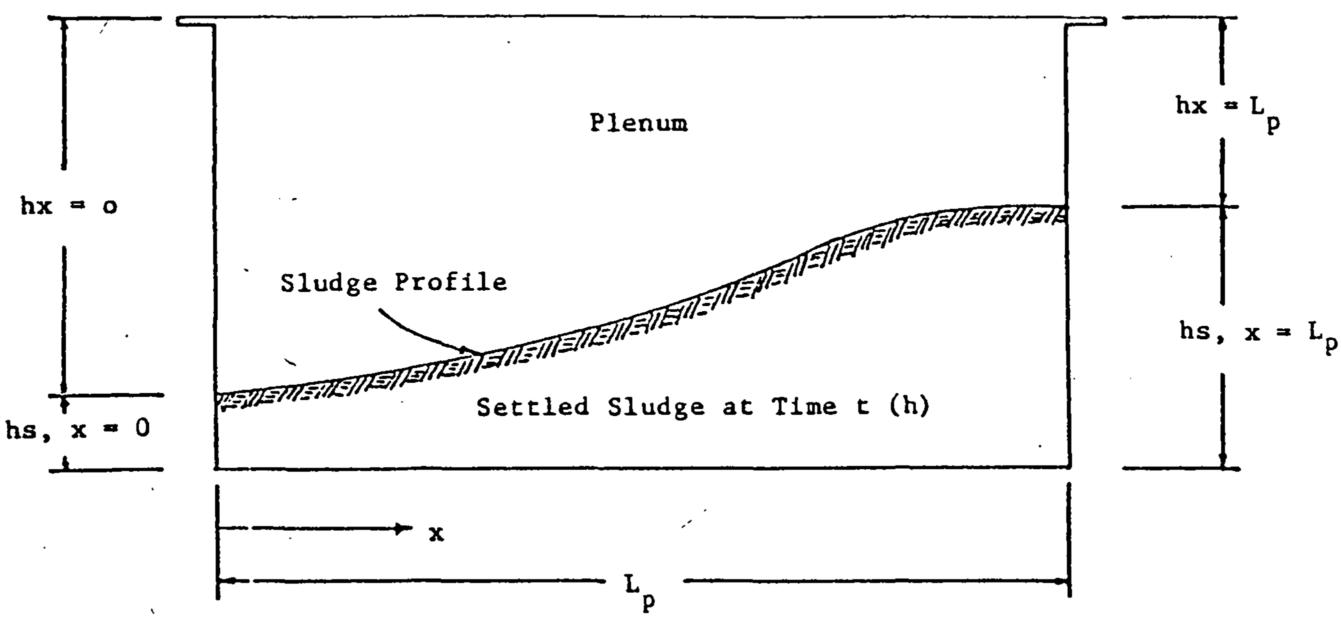


Fig. 3.3 - Sectional View of Plenum

IV EXPERIMENTAL INVESTIGATION

4.1 Background

In 1970, a master plan was prepared by the Metropolitan Water Works Authority (MWWA) of Thailand in response to the increase in water requirements of expanding communities, commercial development and industrial water demands. For these reasons Bang Khen Water Treatment Plant was constructed to serve as the center of water production. In Stage I of Phase I, the plant is designed to provide a capacity of 800,000 m^3/d and by the year of 2000, the production will escalate to 4,800,000 m^3/d.

In this study, all the experiments were conducted in the Bang Khen Water Treatment Plant for the following reasons:

(i) To observe the applicability of the tube-settler in the modern water treatment plant.

(ii) To compare the efficiency of the tube settler system with the solid contact, slurry return type of clarifier at Bang Khen Water Treatment Plant and also to compare the cost-effectiveness of both the systems.

4.2 Raw Water Source

Raw water for the treatment plant is obtained from the Chao Phraya River at Sam Lae Pump Station which is located at tambol Sam Lae, Muang District of Changwat Prathum Thani, about 18 km North of Bang Khen Water Treatment Plant. The raw water is then conveyed by Klong Prapa before the influent conduit to the clarifiers. For this experiment, natural raw water was tapped from the conduit at Clarifier No. 6 and the turbidity of the raw water during the experiment was observed to vary from 25 NTU to 45 NTU. Table 4.1 indicates the raw water characteristics for the month of December and January when the experiment was in progress.

4.3 Experimental Apparatus and Materials

Fig. 4.1 presents a schematic sketch of the experimental set up of the tube settler system. The raw water is obtained from the raw water conduit of the treatment plant. It is then flow by gravity to the constant head tank via a rotameter. The rotameter is employed to ensure a constant flow rate while the constant head tank which has a detention period of 3 minutes provides the necessary hydraulic mixing of the raw water with the alum. This chemically mixed water in then admitted into the flocculator which is equiped with a motor of 1/20 Hp and a speed of 12 rpm.

The steeply inclined tube settler used in this experiment was designed by PANNEERSELVAM (1982). It has a relative length of 18 and an angle of inclination of 60 degrees to the horizontal. The settling unit is made of steel and the tube has dimensions of 5 cm x 5 cm x 90 cm and is made of marine plywood. The total end area of the tubes is 1,500 cm^2. Figure 4.2 gives the detailed dimensions of the unit.

TABLE 4.1

Raw Water Quality of Bang Khen Water Treatment Plant
(December 1982 to January 1983)

Parameter	Range of value (ppm)
Turbidity (NTU)	17 - 60
pH	7.0 - 7.5
Total Alkalinity	64 - 90
Total Solid	170 - 185
Dissolved Solid	100 - 120
Suspended Solid	6 - 69
Total Hardness as CaCo3	84 - 90
Chloride as Chlorine	12 - 14
Free Ammonia - N	0.074 - 0.207
Nitrate - N	NIL
Nitrite - N	0.0006 - 0.0043
Iron	0.29 - 0.38
Manganese	0.01 - 0.263
Magnesium	5.76 - 7.2
Dissolved Oxygen	2.3 - 5.5
BOD5	1.4 - 2.0
Standard Plate Count./100 ml.	790 - 1590

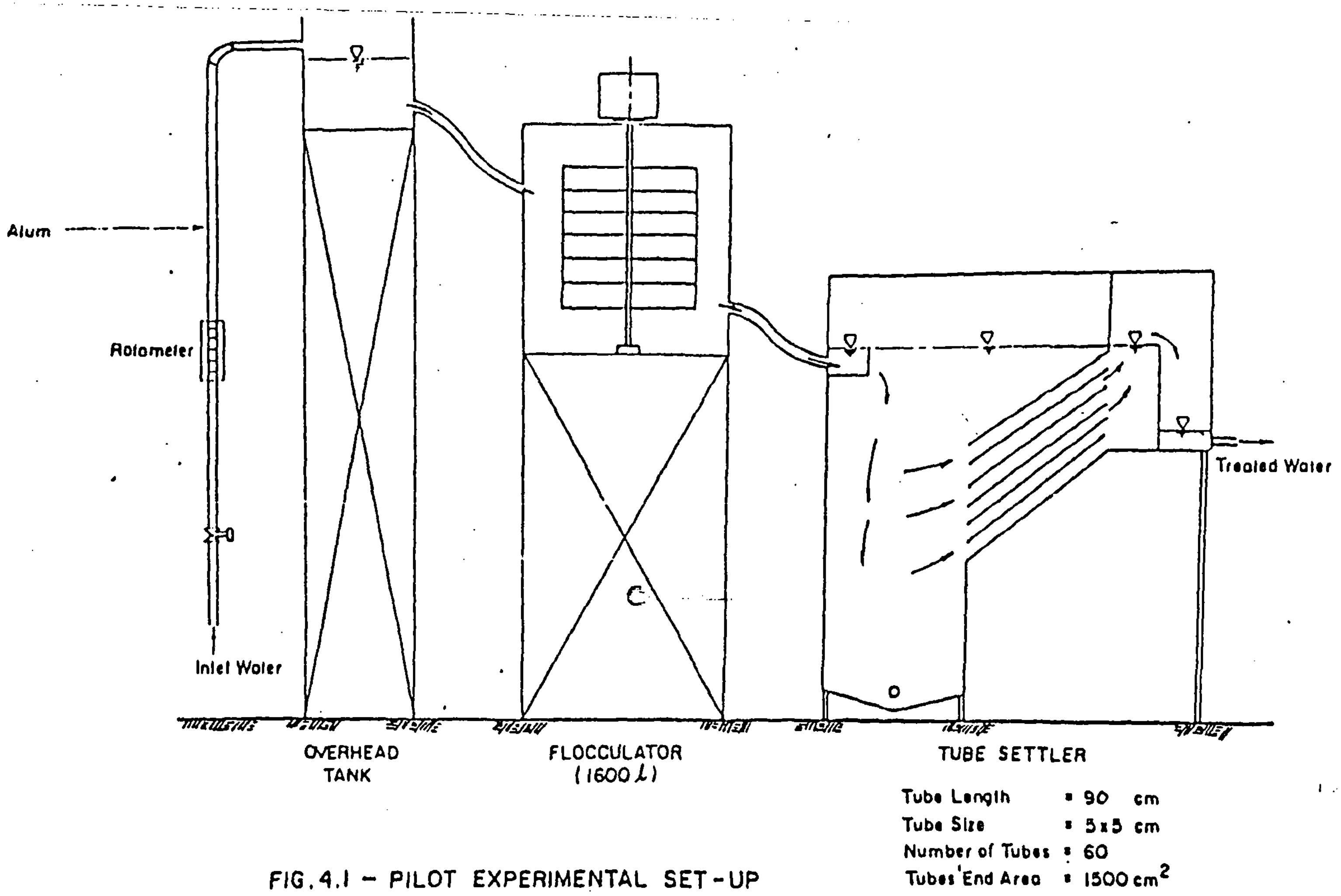


FIG. 4.1 – PILOT EXPERIMENTAL SET-UP

The tank has an inlet chamber at one end and outlet chamber at other end. Both chambers are of 55 cm wide and coupled with triangular weir at the effluent end to facilitate good hydraulic condition at the outlet zone.

The bottom of the tube settler is designed with flange joint to facilitate ease of replacing the plenum bundle of different settling depths. The plenum bundle is provided with a clear PVC window to facilitate measurement of the accumulated sludge depths. A drain pipe was also included for sludge draining.

For column settling analysis, a single sampling level settling column was designed with an internal diameter of 15 cm so as to minimise the wall effect. The column is made of opaque PVC column with a strip of transparent perspex window running from the top of the column to the bottom. A sampling port is located at 5.5 cm from the bottom of the column which is arranged in such a way that samples can be withdrawn from the center of the column.

4.4 Clarifier

In the Bang Khen Water Treatment Plant, the clarifiers are of solid-contact with slurry-recirculation type. Each clarifier has an internal diameter of 58 m and with side water depth just under 5 m. A total detention time is about 100 minutes with approximately 13 minutes detention time provided under the recirculation cone. The loading rate is about 95 m^3/m^2-d. Because of the size of the tanks a center-drive mechanical sludge-scraping equipment is specified. Collected sludge is discharged periodically through alternate sludge blow off lines.

4.5 Methodology

Turbidity was used as the main indicator of the settling performance. HACH Laboratory Turbidity meter of Model 2100A was used for turbidity measurements and the results were then expressed in Nephelometric Turbidity Units (NTUs) which is equivalent of the Formazin Turbidity Units (FTUs) or the Jackson Turbidity Units (JTUs).

4.5.1 Preliminary Analyses

In the preliminary analyses, the optimum alum concentration for each turbidity range was determined using conventional jar test apparatus. The optimum concentrations of alum will be later used in the evaluation of the tube settler performance. Also, the effect of polyelectrolyte addition upon the settling performance was being tested. Several different types of polyelectrolytes such as CAT-FLOC T (cationic), SUPERFLOC (anionic), and Poly Aluminum Chloride (PAC) were used.

4.5.2 Pilot Scale Investigation

In the tube settling experiment, the tube settling tank was first filled to the overflow level with tap water. Raw water was then admitted into the constant head tank, simultaneously desirable alum concentration was injected. Rapid mixing due to flow agitation was accomplished after the point of chemical injection. The coagulated raw water was then admitted to the flocculator where further coagulation and flocculation take place. The flocculated water was then introduced to the tube settler for sedimentation.

Raw water, flocculated water and clarified water were then sampled in hourly intervals. For each run, the experiment was terminated once the effluent turbidity reached an approximate constant value.

During the experiment, the following flows were used: 2 ℓ/min, 5 ℓ/min, 10 ℓ/min, 15 ℓ/min, 20 ℓ/min. In the case of the plenum design, the settled sludge depths across the plenum length (i.e. X1 = 0 cm, X2 = 8 cm, X3 = 16 cm, X4 = 24 cm, X5 = 32 cm) were measured for each flow velocity. Also, the efficiency of the tube settler for each flow rate was recorded.

4.5.3 Column Settling Analysis

The experimental study was conducted in a form of quiescent settling on a batch basis. Natural flocculated water was used for the experiment and the raw water turbidity ranges from 25 NTU to 45 NTU during the period of experiment. The experiment was carried out with the following assumption:

(a) Temperature variation was between a small range of 27°C to 33°C, thus the effect of thermal current upon the percent of removal was considered to be negligible.

(b) The distribution of the flocculated particles is homogeneous within the settling column at the start of the experiment.

(c) All particles begin to settle as soon as the process start.

For each experimental run, the settling column was first filled with raw water to the marked desired level from the sampling port. The sample in the column was then thoroughly mixed to obtain a uniform suspension. For such size of column, an air diffuser located at the bottom of the column is necessary to provide effective mixing. Optimum alum dose was then added before flocculation took place and allowed to settle in quiescent condition. Zero time was set as soon as flocculation was completed. Sample were then withdrawn through the sampling port at time intervals of: 15 min, 30 min, 45 min, 1 h, 2 h, 3 h, 4 h, 5 h, and 6 h. The turbidity of each sample was measured and the percent turbidity removal was then computed.

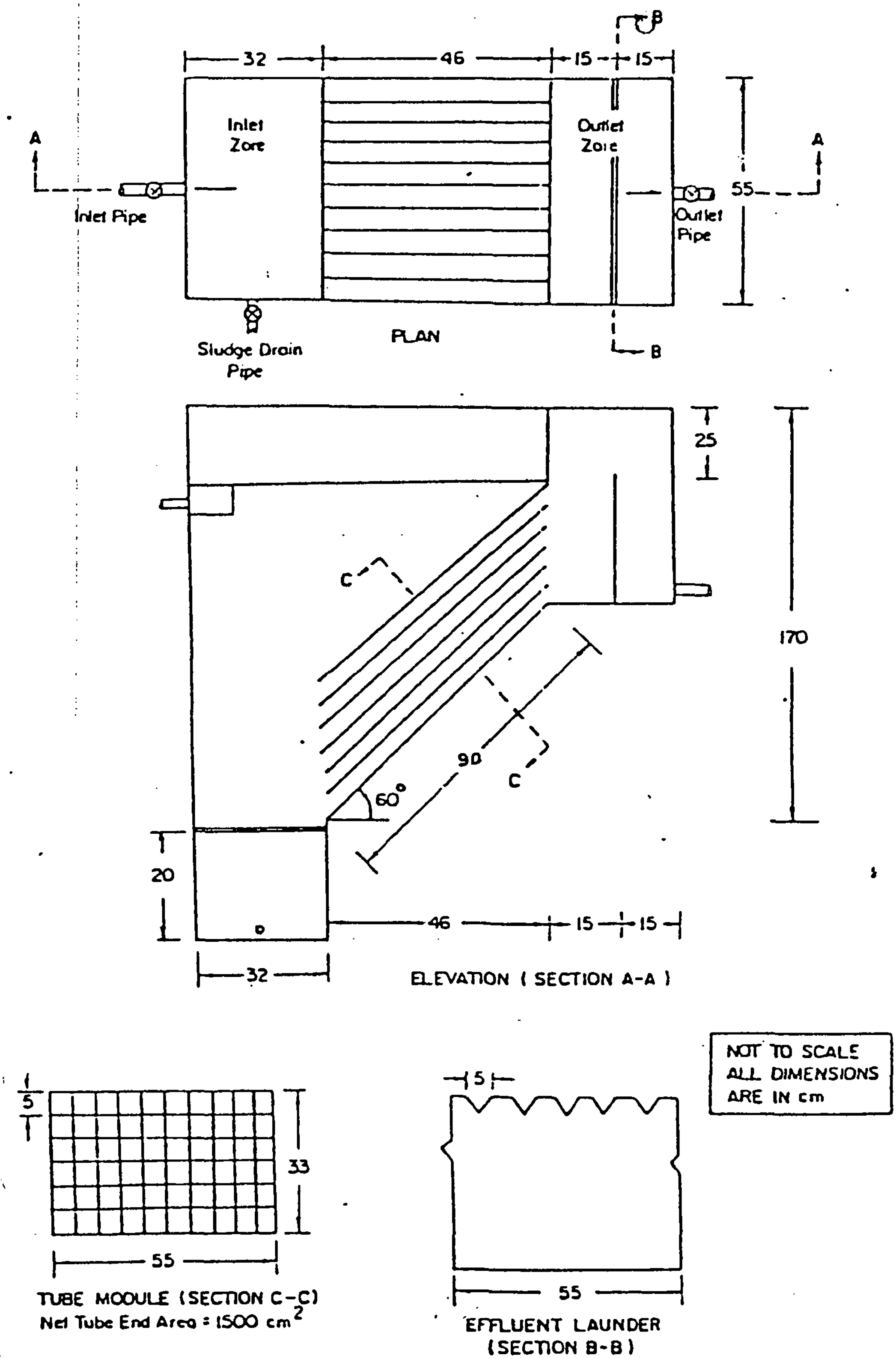


FIG. 4.2 – DETAILS OF INCLINED TUBE SETTLER.

V PRESENTATION AND DISCUSSION OF RESULTS

The data obtained from all experiments are presented in Appendices A, B, C, and D. This section will devote mostly to the presentation and discussion of the analysed results.

5.1 Preliminary Analytical Results

To determine the optimum alum concentration and to find out the effect of polyelectrolytes upon the flocculation process, jar test technique which was proposed by AMIN (1976) was used. The modified procedure consists of fast mixing at 100 rpm for 1 minute followed by slow mixing at 12 rpm for 30 minutes and 10 minutes for flocculation and sedimentation. This procedure was deviced to match the pilot scale flocculator used in the experiment.

For all experiments, no pH adjustment was necessary since the pH of the raw water was within the neutrality range (i.e. 7-8). Table A1-1, A1-2, A1-3, (see Appendix A) show the optimum alum concentration of 28 mg/ℓ, 28 mg/ℓ, and 34 mg/ℓ for raw water turbidities of 25 NTU, 40 NTU and 56 NTU, respectively. Table A1-1 also illustrates that if the flocculation and sedimentation time of the pilot scale flocculator could be increased from 10 minutes to 30 minutes, then better percent turbidity removal could be accomplished. Figure 5.1 shows the typical plot of residual turbidity against the alum concentration for raw water turbidity of 25 NTU.

Currently, many authors claim that addition of polyelectrolyte could enhance settling performance. On the other hand many researches concluded that addition of polyelectrolyte does not improve the process. From this study, the results show that polyelectrolytes either of cationic or annionic in nature do not significantly improve the settling performance. Table A2-1 (Appendix A) indicates that addition of CAT-FLOC T at optimum alum dose could only bring the residual turbidity down from 3.0 NTU to 2.6 NTU. Table A2-2 (Appendix A) also confirms that anionic polyelectrolyte such as SUPERFLOC has no significant effect upon the residual turbidity.

Poly Aluminum Chloride (PAC), was also used in the experiment and although PAC could achieve the same residual turbidity at lower dosage than the alum, but due to the high cost of PAC which is four times that of alum, make it unattractive to most treatment plants.

5.2 Overflow Rate Versus Efficiency

It is universally accepted that the design of a conventional settling tank for water and wastewater treatment is based on the overflow rate, which is expressed as the rate of flow per unit surface area. The same concept is being adopted in high rate sedimentation.

Figure 5.2 presents the results of all experimental runs, showing the turbidity removal efficiency at various computed overflow rates. As expected, the removal efficiency decreases with the increase of overflow rate. It appears that higher raw water turbidity tends to provide better removal efficiency than those of lower turbidity.

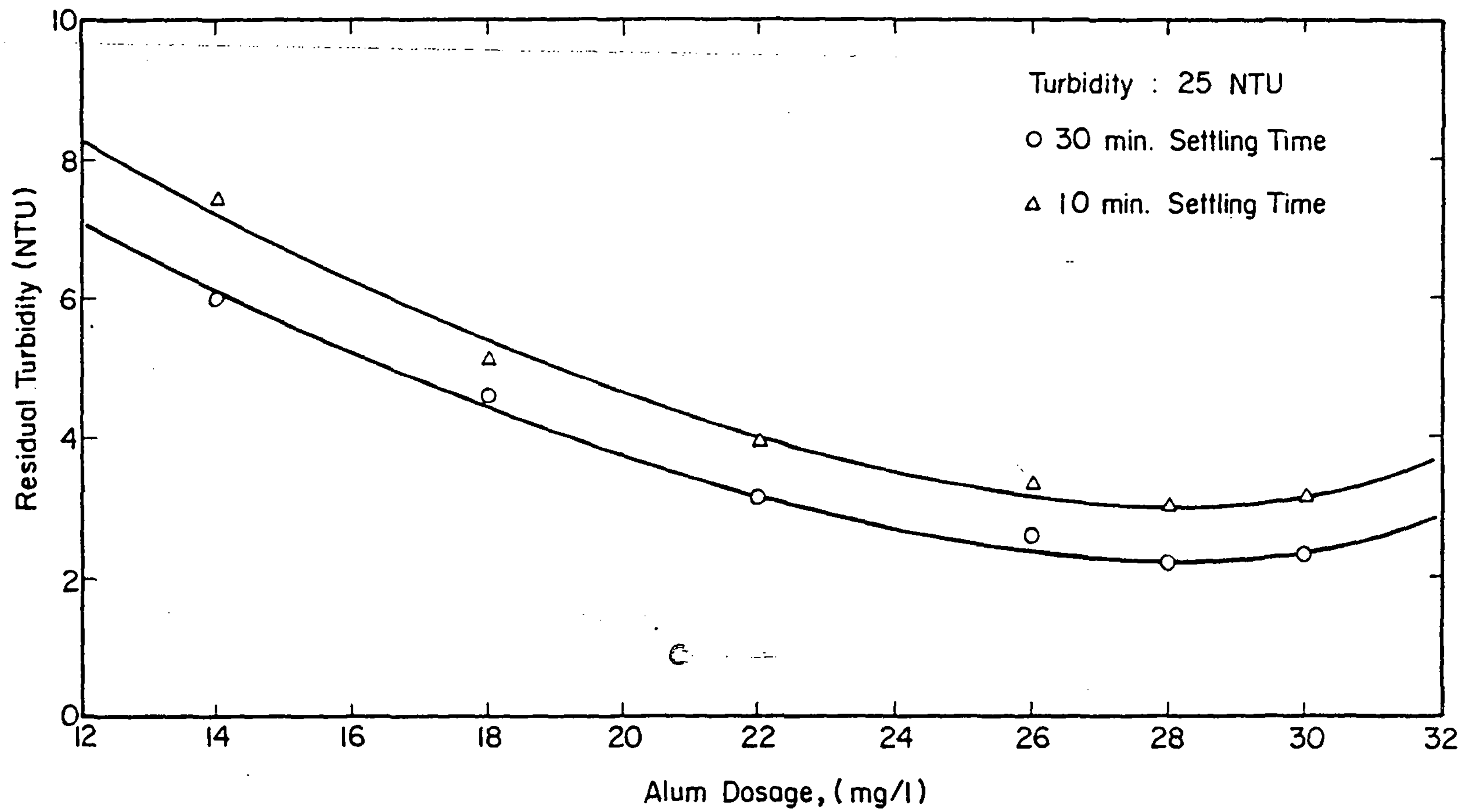


Fig. 5.1 — Determination of Optimum Alum Dosage

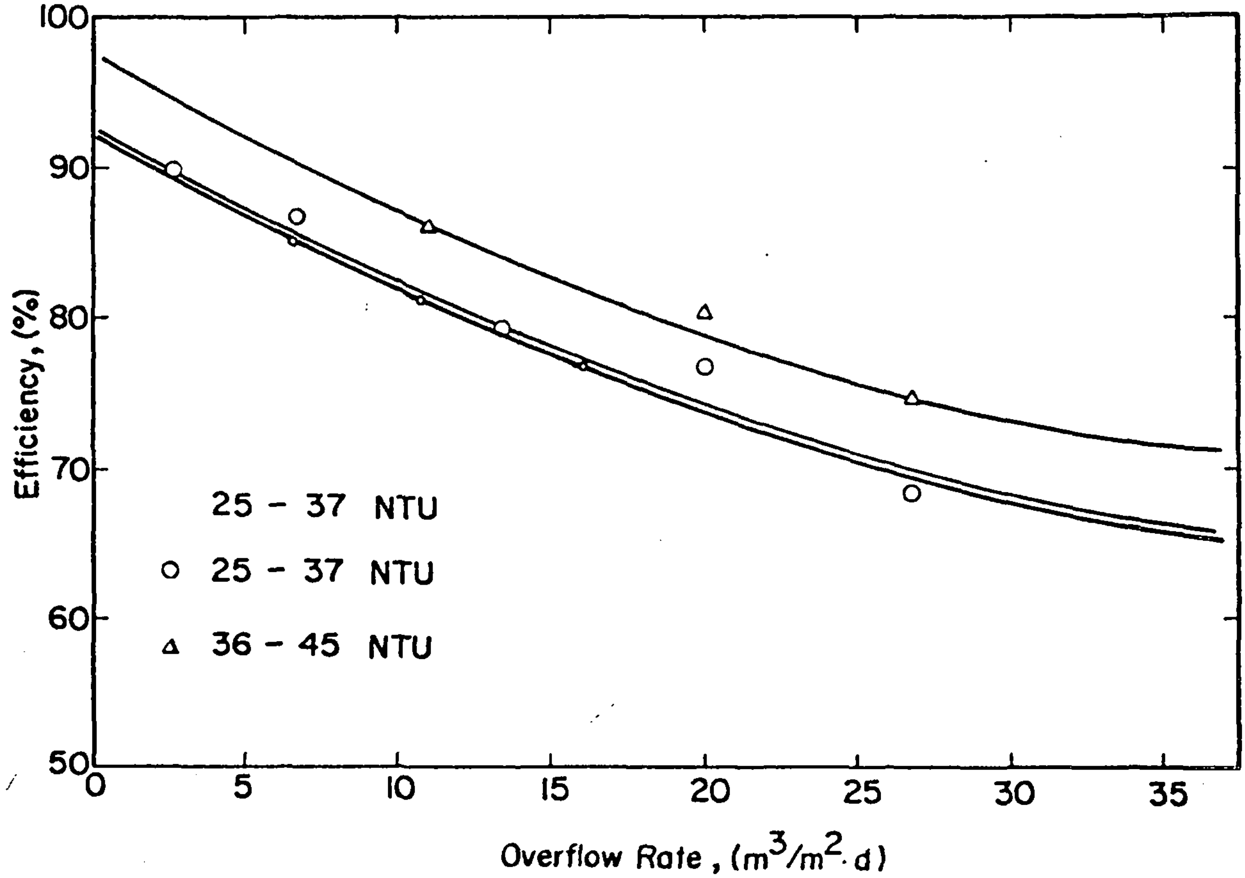


Fig. 5.2 – Effect of Overflow Rate on Efficiency

Table 5.1 gives the comparison of results obtained by several other researchers and the present study. Although in each individual case, different experimental conditions exist, yet the results of the present study are in close agreement with the findings of previous works.

Fig. 5.3 indicates the effluent quality of the calrified water versus the overflow rates. Three curves having alum concentrations of 22 mg/ℓ, 28 mg/ℓ and 32 mg/ℓ were observed. In the Bang Khen Water Treatment Plant, the Authority insists upon the clarified water that should be equal to or less than 5 NTU before it is allowed to enter the filter system. This criteria is to safeguard the filter system from overloading. From the graph, at optimum alum dose of 28 mg/ℓ, overflow rate of 8.75 m^3/m^2-d will provide water effluent of 5 NTU. In Bang Khen Water Treatment Plant, "economic" alum dose of 22 mg/ℓ is used (during the course of study) to provide effluent quality of 5 NTU. Therefore to cater for such situation, alum concentration of 22 mg/ℓ was also used to perform tube settler experimental runs. Fig. 5.3 shows that at 22 mg/ℓ of alum dose, overflow rate of 8.0 m^3/m^2-d will provide effluent quality of 5 NTU. The above experimental comparison is essential in the later section where comparison of costs between the conventional sedimentation tank and the tube settler system needs to be analysed.

TABLE 5.1

Comparison of Percent Turbidity Removal for Various Overflow Rates Investigated by Some Authors

Overflow Rate (m^3/m^2 d)	Raw water Turbidity (NTU)	YAO (1973)	VASANAD-ILOKLERT (1978)	CHEN (1979)	PANNEER-SELVAM (1982)	Present Study (1983)
Nature of water		N.R.W.	N.R.W.	S.R.W.	S.R.W.	N.R.W.
13	20	85.00%	-	83.50%	-	-
	30	-	-	-	-	82.25%
	40	-	-	91.00%	-	-
	50	90.00%	-	-	84.40%	84.50%
	60	-	69.00%	-	-	-
20	20	-	-	79.00%	-	-
	30	82.50%	-	-	-	74.25%
	40	-	-	88.00%	-	-
	50	88.00%	-	80.60%	-	79.00%

N.R.W. = Natural Raw Water   S.R.W. = Synthetic Raw Water

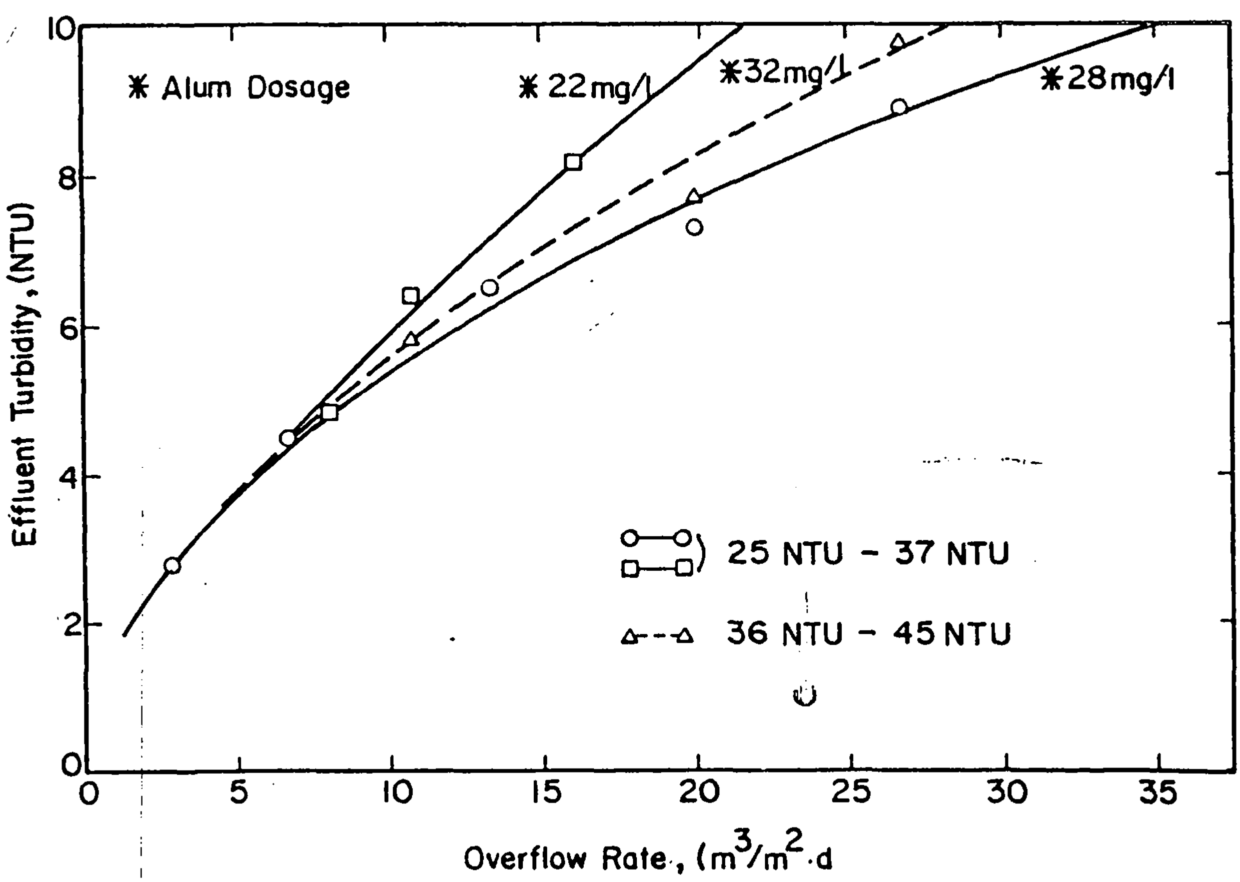


Fig. 5.3 - Effluent Turbidity vs Overflow Rate

If 80% removal efficiency is acceptable, then a design overflow rate of 12.75 m^3/m^2-d for raw water turbidity of 25-37 NTU and 18.5 m^3/m^2-d for raw water turbidity of 36-47 NTU can be used within the limits of experimental conditions.

If effluent quality of 5 NTU is insisted, then the overflow rate of 8.75 m^3/m^2-d and 8.5 m^3/m^2-d for raw water turbidity of 25-37 NTU and 36-45 NTU, respectively under the optimum alum dosage. For "economical" alum dose, overflow rate of 8.0 m^3/m^2-d is recommended for raw water turbidity range of 25-37 NTU.

Table 5.2 shows the practical operational overflow rates for most experimental conditions.

TABLE 5.2
The Performance of the Inclined Tube Settler at Various Overflow Rates, Alum Dose, and Raw Water Turbidity

Raw Water Turbidity (NTU)	Alum Dose (mg/l)	Overflow Rate (m^3/m^2 d)	Efficiency %	Effluent Quality (NTU)
25-37	22	8.00	83.00	5.0
	28	8.00 8.75	84.30 83.60	4.8 5.0
36-45	32	8.50	88.50	5.0
25-37	28	12.75	80.00	7.9
36-45	32	18.50	80.00	8.8

Since the removal efficiency is a function of overflow rate (for all other parameters are fixed), a regression analysis was used to produce formulations which fit best for the experimental data obtained for removal efficiency and overflow rate.

For raw water turbidity of 25-37 NTU,

$$\ln E = 4.52993 - 0.01140 \times Vsc \qquad (5.1)$$

Correlation factor for this relationship was found to be 97.65%.

For raw water turbidity of 36-45 NTU,

$$\ln E = 4.55008 - 0.00873 \times Vsc \qquad (5.2)$$

Correlation factor for this relationship was found to be 98.30%.

Fig. 5.4 shows the regressed values for both the turbidity range and Table B5-1 and B5-2 (Appendix B) show the mathematical calculations using the Least Squares Method to arrive at the formulations.

5.3 Effect of Turbidity on Efficiency

Fig. 5.2 shows the removal efficiency curves for raw water turbidity of 25-37 NTU and 36-45 NTU. The figure demonstrates that the removal efficiency increases with the increase of raw water turbidity for all overflow rates. The reasons for this improvement in efficiency could be due to better flocculation before sedimentation, or better aggregation during settling. Both of these result in the formation of heavier or larger floc particles. However, it is important to note that higher removal efficiency at higher influent turbidity does not automatically mean a lower effluent turbidity as provided in the case of lower influent turbidity. Fig. 5.2 confirms such important observation.

5.4 Effect of Flow Velocity on Efficiency

In this research, flow velocity of 0.8 m^3/m^2-h, 2 m^3/m^2-h, 4 m^3/m^2-h, 6 m^3/m^2-h, and 8 m^3/m^2-h were used as shown in Table B6-1 (Appendix B). Fig. 5.5 shows that as the flow velocity increases, the percent turbidity removal decreases, this high flow velocity causes resuspension of settled particles and also scouring of the settled sludge surface.

Table 5.3 shows the comparison of present study with the works done by PANNEERSELVAM (1982), the results of both the studies concluded that synthetic raw water does provided better settling performance than the natural raw water. This could be due to natural raw water contains more colloidal particles than that of synthetic raw water. The table also reviews that for the same flow velocity, high efficiency could be achieved for higher raw water turbidity.

As mentioned in section 5.2, if 80% turbidity removal is acceptable, then the flow velocity of 3.87 m^3/m^2-h and 5.43 m^3/m^2-h are recommended for raw water turbidity of 25-37 NTU and 36-45 NTU, respectively under the optimum alum dose. If to comply with the effluent requirement of 5 NTU, the flow velocity of 2.67 m^3/m^2-h and 2.55 m^3/m^2-h should be resorted to for raw water turbidity of 25-37 NTU and 36-45 NTU, respectively.

5.5 Experimental Results of Plenum Design

Preliminary experiment confirmed that plenum bundle of 20 cm depth could be used to provide data which is necessary for the derivation of empirical formulae for the plenum design.

Appendix D includes Table D1-1 to Table D1-3. Each table contains the data of the operation of tube settler at certain flow velocity and the percent turbidity removal and the sludge depth across the plenum length at X1 = 0.0 cm, X2 = 8 cm, X3 = 16 cm, X4 = 24 cm, and X5 = 32 cm were

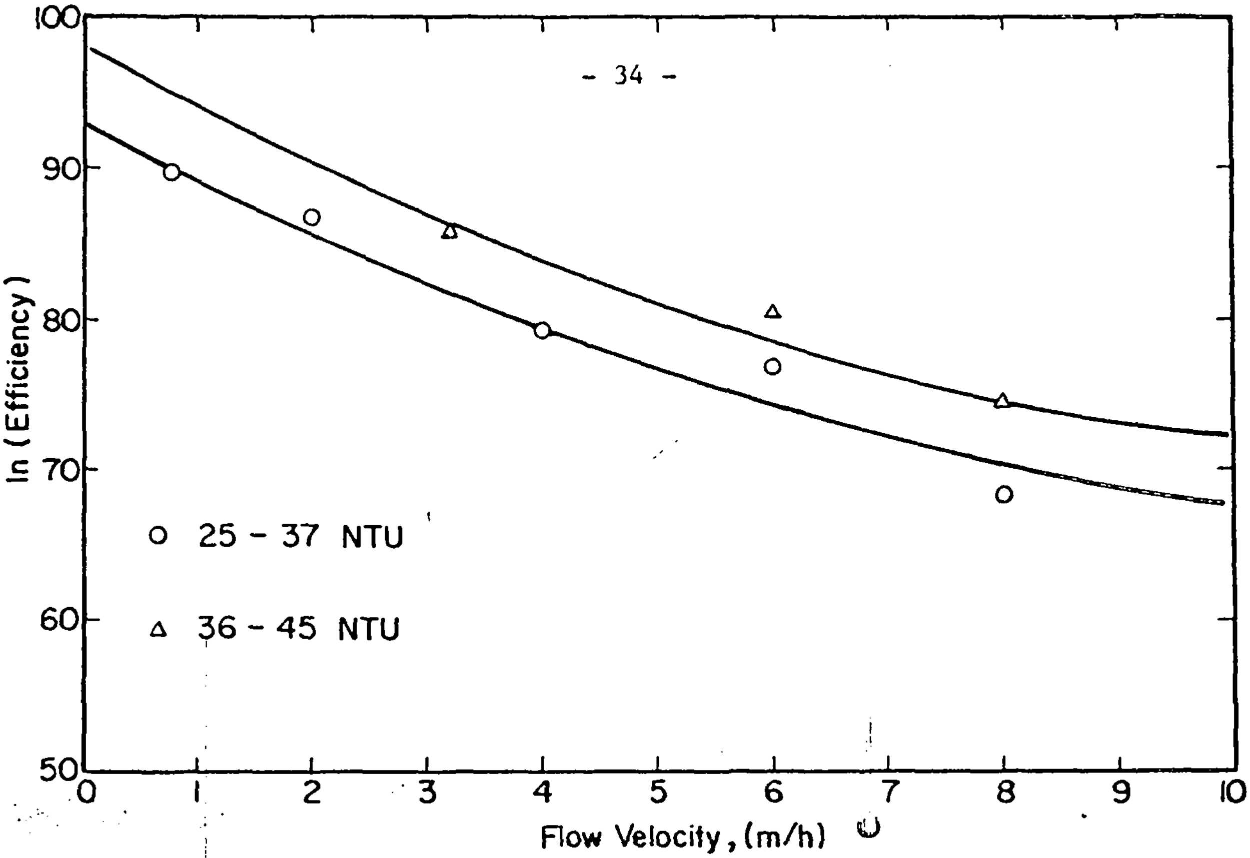


Fig. 5.4 – Effect of Flow Velocity on Efficiency

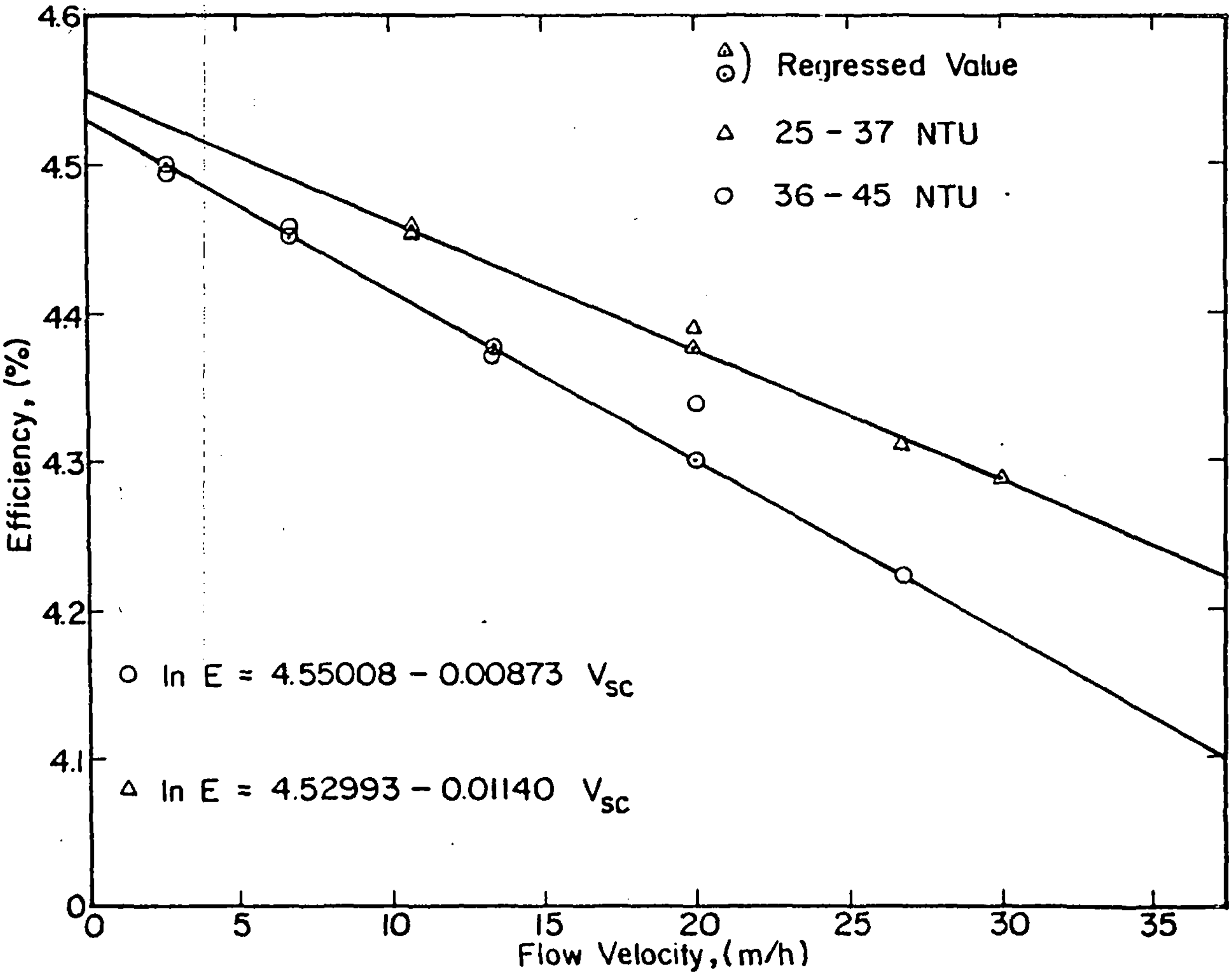


Fig. 5.5 – ln (Efficiency) vs Overflow Rate

TABLE 5-3

Comparison between Present Study with PANNEERSELVAM Findings

Velocity (m^3/m^2-h)		0.8	2.0	3.2	4.0	5.6	6.0	8.0
PANNEERSELVAM[1] (1982)	Influent Turbidity	-	60	-	66	72	-	68
	Percent Removal	-	90	-	85	83	-	79
SOW[2] (1983)	Influent Turbidity	25 NTU to 37 NTU						
	Percent Removal	89.6	86.7	-	79.2	-	76.8	66.3
	Influent Turbidity	36 NTU to 45 NTU						
	Percent Removal	-	85.6	-	-	-	80.4	74.4

[1] PANNEERSELVAM: Synthetic raw water was used

[2] SOW : Natural raw water was used.

recorded. The hourly samplings proceeded until the efficiency of turbidity removal deviates drastically from the approximate constant value.

Figure 5.6 summarises all informations regarding the percent turbidity removal and the operation time. From the curves, it is obvious that at 21 hours, 11 hours, and 8 hours of operation at flow velocity of 3.2 m^3/m^2-h, 6 m^3/m^2-h and 8 m^3/m^2-h, respectively, the effluent turbidity begins to deteriorate, hence the efficiency of the tube settler starts to decrease. These phenomenon could be due to the occurrence of turbulent flow in the tube settler plenum or could be the consequence of sludge scouring at the plenum.

Table 5.4 indicates the sludge depths at various distance Xs across the plenum width after 8 hours of operation. The settled sludge profile for each flow velocity is as shown in Figure 5.7. Higher the flow velocity, faster the settled sludge depth reaches it critical plenum depth. This implies that if operated at higher flow velocity, deeper plenum blundle should be provided for the same number of operation hours as for those with low flow velocity.

Figure 5.8 reviews the relationships between flow velocity against the depth of settled sludge at the entrance and at the exit of the plenum bundle. Due to the importance of predicting the sludge depth, regression analysis 'Least Squares Method', was used to derive empirical formulae for sludge

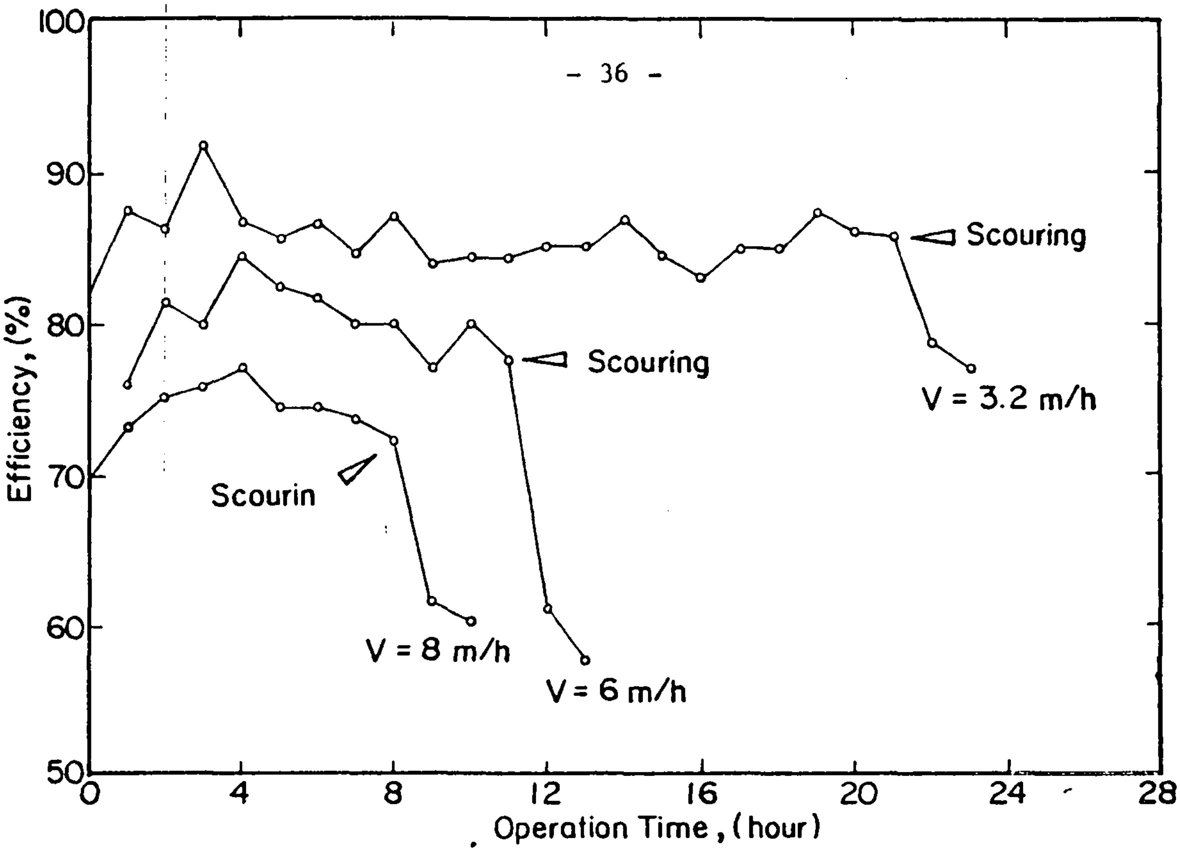


Fig. 5.6 – Efficiency vs Operation Time for Plenum Design

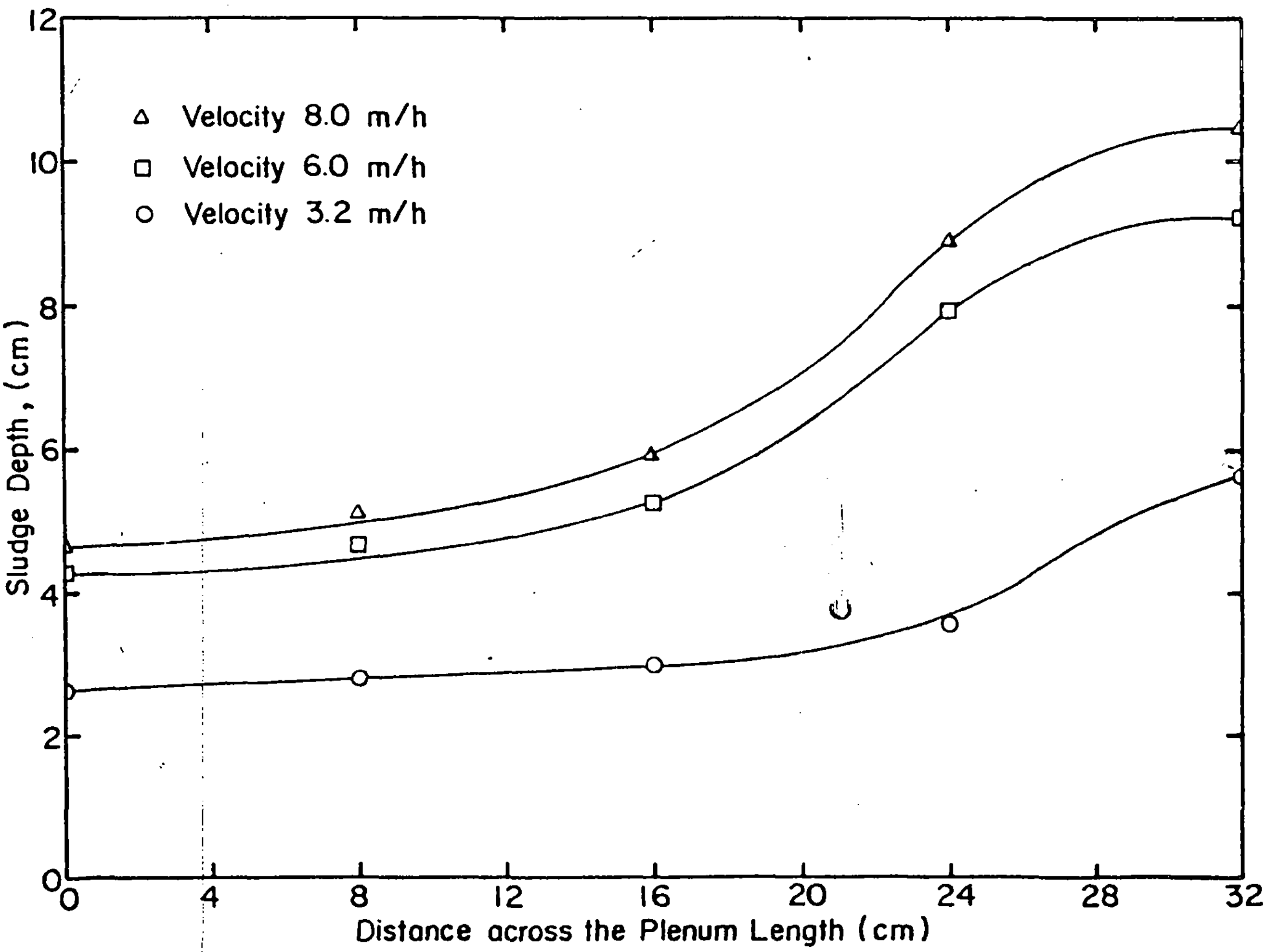


Fig. 5.7 – Sludge Profile after 8 Hours of Operation

TABLE 5.4 Settled Sludge Depth After 8 Hours of Continuous Operation at Various Velocities

Flow (l/min)	Flow Velocity (m^3/m^2 h)	Sludge Depth After 8 Hours of Operation (cm)				
		X1	X2	X3	X4	X5
8.00	3.2	2.65	2.80	3.00	3.55	5.65
15.0	6.0	4.30	4.65	5.25	7.90	9.20
20.0	8.0	4.65	5.10	5.90	8.90	10.45

depth as a function of time and the flow velocity. Fig. 5.9 illustrates the regressed values of ln (Sludge Depth) versus ln (Velocity).

For 8 hours of operation and for turbidity range of 36-40 NTU,

$$hs,\ x = 0\ (cm) = 1.28499 \times V^{0.68917} \qquad (5.3)$$

$$hs,\ x = 32\ (cm) = 2.57147 \times V^{0.68808} \qquad (5.4)$$

where hs, x = 0 is the settled sludge depth at x = 0 cm,

hs, x = 32 is the settled sludge depth at x = 32 cm.

For t hour of operation, Table E1-2 (Appendix E) confirms that

$$hs,\ x = 0\ (cm) = 1.28499 \times V^{0.63917}\ (t/8) \qquad (5.5)$$

$$hs,\ x = 32\ (cm) = 2.57147 \times V^{0.68808}\ (t/8) \qquad (5.6)$$

In order to have general formulations, it is necessary to take into account of the length of the plenum and the vertical thickness of the tube blundle. According to Figure D2 (Appendix D), equations (5.5) and (5.6) can be replaced by

$$hs,\ x = 0\ (cm) = 1.28499 \times V\ (t/8)(32/Lp)(a/33) \qquad (5.7)$$

$$hs,\ x = Lp\ (cm) = 2.57147 \times V\ (t/8)(32/Lp)(a/33) \qquad (5.8)$$

where Lp = length of the plenum

a = vertical distance of the tube bundle.

In this study, the formula derived by CHEN (1979) can not be verified due to the fact that for X = 1 which is the critical condition, the formula (equation 3.17) derived by him cannot take this into consideration. Table

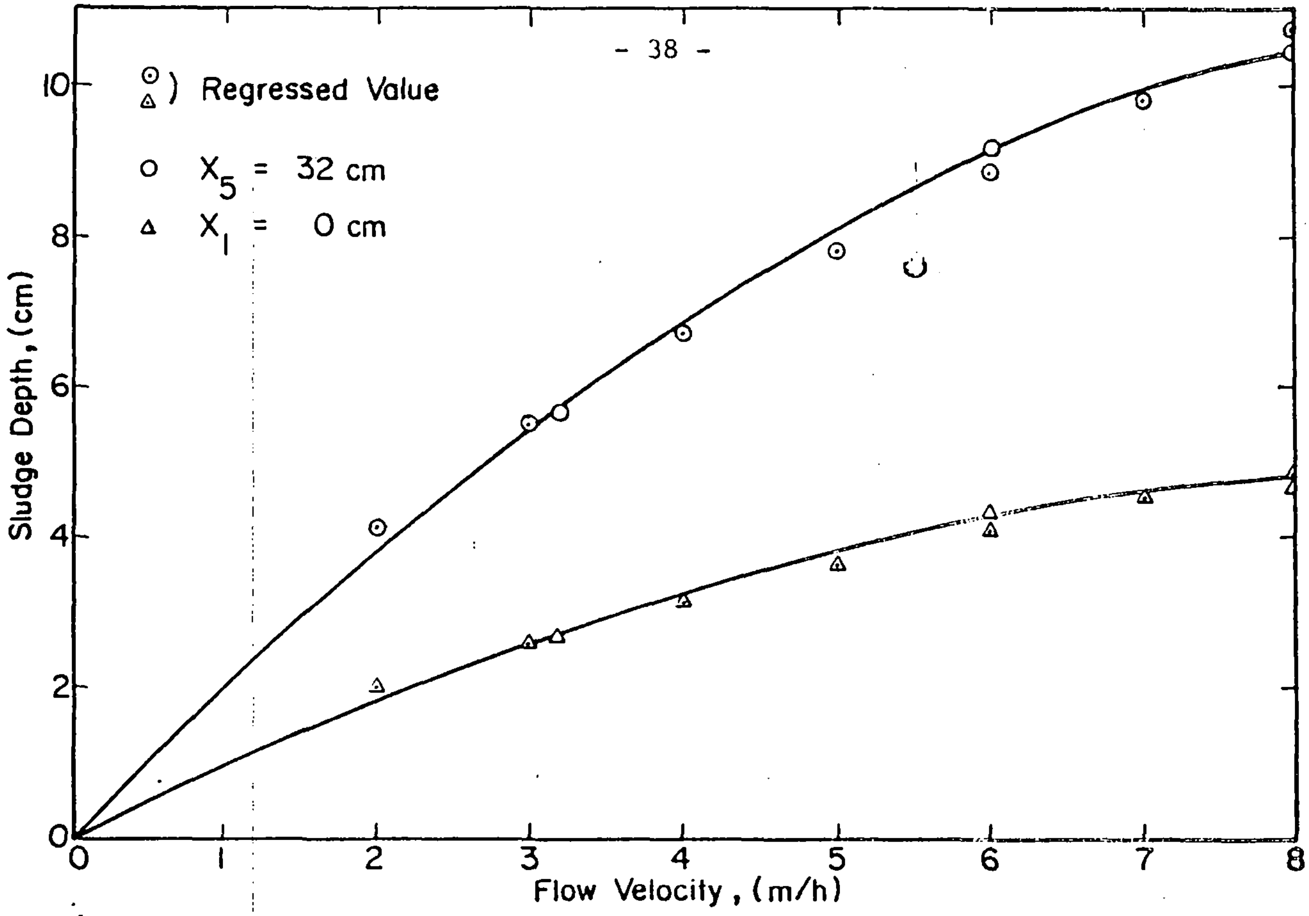
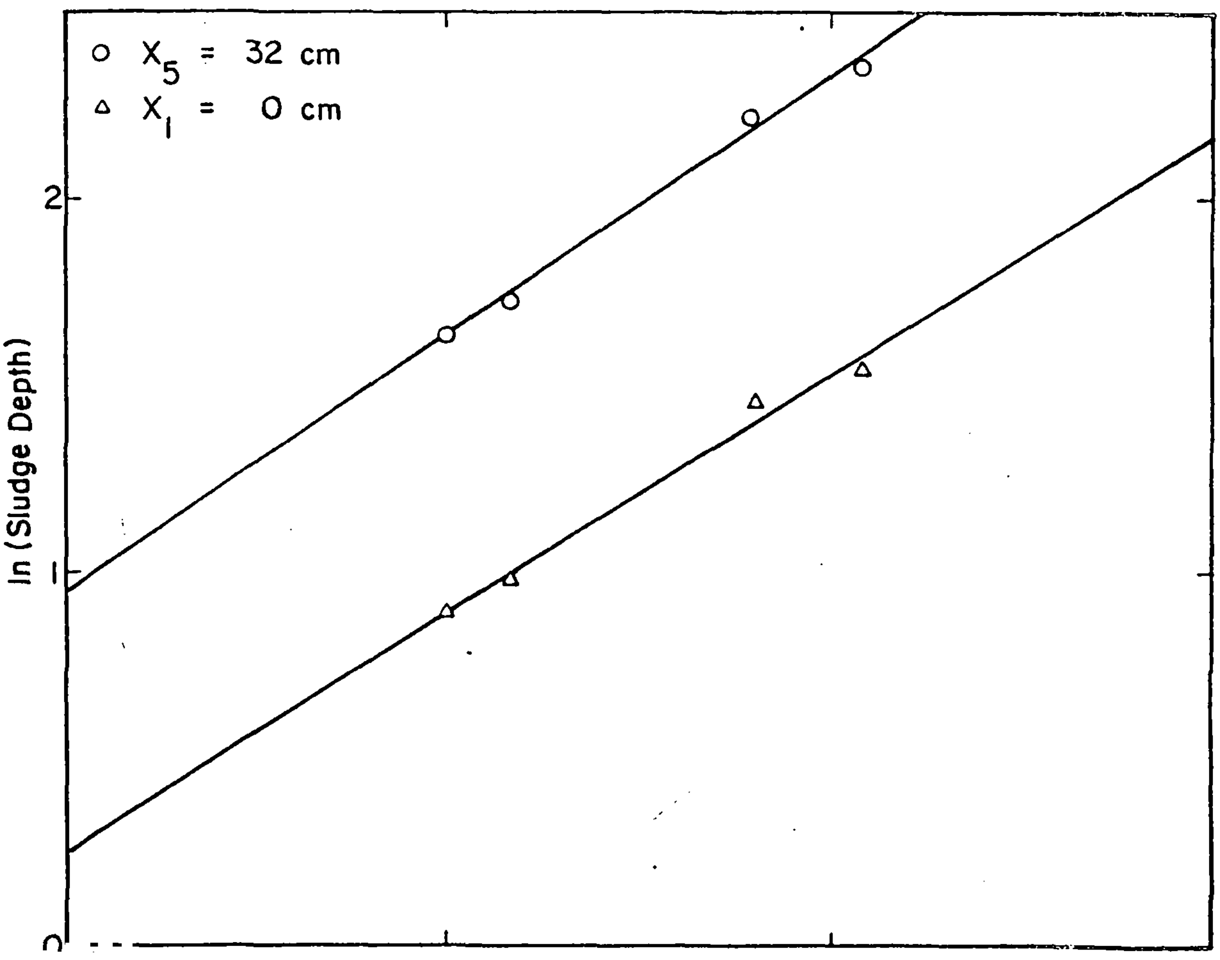


Fig. 5.8 – Sludge Depth vs Flow Velocity



5.5 shows the critical plenum depth at various flow velocities that were obtained from the experiment. Figure 5.10 illustrates the plot of flow velocity versus the critical plenum depth for X = 0 cm and X = 32 cm. Least Squares Method was used to fix the curves, which give:

$$hx = 0 \ \text{(cm)} = 14.92354 \times V^{0.13574} \tag{5.9}$$

$$hx = 32 \ \text{(cm)} = 4.29316 \times V^{0.57992} \tag{5.10}$$

Correlation factor of 99.08% for both cases and V is in terms of m/h. Therefore, for time t, flow velocity V, the total minimum depth at entrance and at plenum exit (i.e. X = 1 cm),

$$Hx = 0 \ \text{(cm)} = 1.28499 \times V^{0.63917} (t/8)(32/Lp)(a/33) \quad (5.11)$$
$$+ 14.9235 \times V^{0.13574} \quad (5.11)$$

$$Hx = 32 \ \text{(cm)} = 2.57147 \times V^{0.68808} (t/8)(32/Lp)(a/33)$$
$$+ 4.29316 \times V^{0.57992} \quad (5.12)$$

Appendix E shows the details calculations of all functions involving Least Squares Method of analysis in this section.

TABLE 5.5

Critical Plenum Depth Across the Plenum Width for Various Flow Velocity

Raw Water Tyrbidity : 36-45 NTU
Plenum bundle Used : 20 cm
Alum Dose : 28 mg/l

Flow (l/min)	Flow Velocity (m^3/m^2 h)	Critical Plenum Depth (cm)				
		X1	X2	X3	X4	X5
8.00	3.2	17.35	17.10	15.60	11.55	8.350
15.0	6.0	18.95	17.95	16.85	13.15	12.50
20.0	8.0	19.85	19.45	18.60	15.60	14.05

Table 5.6 shows the comparison of the total plenum depths obtained by PANNEERSELVAM (1982) and the present study by assuming appropriate values for all necessary parameters. The frequency of desludging is assumed to be 2 days. The results from the table review that the values obtained in accordance to PANNEERSELVAM findings yield lower magnitude than the results of the present study for the total plenum depths. There are several reasons

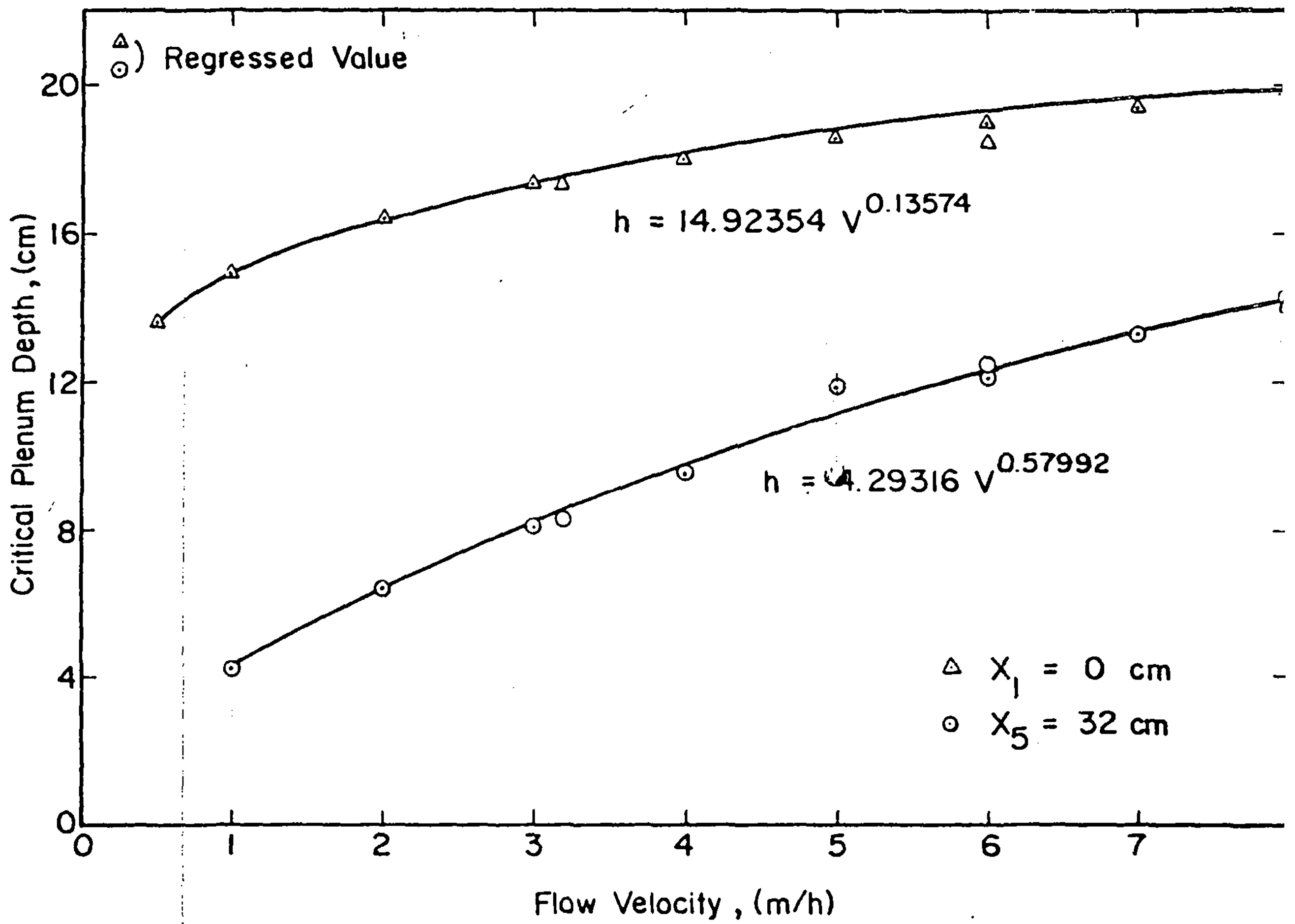


Fig. 5.10 — Critical Plenum Depth vs Flow Velocity

TABLE 5.6
Comparison of the Total Plenum Depth Obtained by PANNEERSELVAM and the Present Study

Parameter	PANNEERSELVAM[5]	Present Study[6]
Capacity (m^3/d)	1000	1000
Flow Velocity (m^3/m^2 h)	4	4
a (Width in cm)	320	320
Lp (plenum length in cm)	100	100
t (frequency of desludge)	2 days	2 days
Total plenum depth at entrance (cm)	37.6[1]	76.04[3]
Total plenum depth at x=l (cm)	78.02[2]	133.87[4]

[1] $H_{x=0}$ (cm) $= 0.877 \times V^{0.672} (t/10)(32/Lp)(a/33) + h_o$

[2] $H_{x=Lp}$ (cm) $= 0.979 \times V^{1.072} (t/10)(32/Lp)(a/33) + h_{x=0}(1 - x/Lp)^{0.1}$

[3] $H_{x=0}$ (cm) $= 1.28499 \times V^{0.63917} (t/8)(32/Lp)(a/33) + 14.9235 \times V^{0.13574}$

[4] $H_{x=Lp}$ (cm) $= 2.57147 \times V^{0.68808} (t/8)(32/Lp)(a/33) + 4.29316 \times V^{0.57992}$

[5] Synthetic Raw Water was Used

[6] Natural Raw Water was Used

which contributed to the above differences. Firstly, PANNEERSELVAM conducted the experiment based on 10 hours of operation, and during that 10 hours period, three different flow velocities were used and toward the transitional point for each velocity, the settled sludge depths at entrance and at x = 3/4 ℓ along the plenum length were measured. But the final equations arrived at by him for the settled sludge depths, i.e.

$$h_{x=0}\ (cm) = 0.8770 \times V^{0.672}\ (t/10)(32/Lp)(a/33) \qquad (5.13)$$

$$h_{x=Lp}\ (cm) = 0.9792 \times V^{1.072}\ (t/10)(32/Lp)(a/33) \qquad (5.14)$$

These equations are based on only single flow velocity for the 10 hours of operation period, thus contradict the experimental conditions. Other subsidary reasons which contribute to the differences are:

(1) the value of $h_{x=0} = C_oQ_o$ postulated by CHEN (1979) is low as compared to the findings of the present study.

(2) in the derivation of the critical plenum depth equations, i.e.

$$h_{x=0} = h_o(1 - x/Lp)^{0.1} = h_o \qquad (5.15)$$

(PANNEERSELVAM, 1982)

$$h_{x=1} = h_o(1 - x/Lp)^{0.1} \qquad (5.16)$$

the value of n was chosen based on only one flow velocity (optimum velocity), thus the value of 0.1 for the equations above does not represent the actual situation.

5.6 Column Settling Results

Appendix C presents the results obtained in batch column settling of the natural raw water. Each table in the Appendix C contains informations regarding the column height, sampling time, the effective height of the flocculated water and the effluent turbidity. These data were then processed and transformed into the respective overflow rate and percent of turbidity removal. For all the experimental runs, optimum alum concentration of 28 mg/ℓ was used.

Fig. 5.11 shows the plot of percent turbidity removal versus the overflow rate for the settling column of depths 10 cm, 30 cm, 50 cm, 70 cm, and 100 cm. The graph also includes the curve of percent turbidity removal against the overflow rate for the tube settler system which can be used as the basis of comparison.

From Fig. 5.11, it is obvious that the general trend of the column settling results obtained from shallow settling column of depths 10 cm to 50 cm follow very closely to that of the tube settler system. This indicates that the parameter overflow rate computed by YAO (1973) for tube settler has similar characteristic to that of the column settling. But as the depth of the settling column increases, the deviation of results from the tube settler performance seems to be significant. This graph also reviews that flocculation and sedimentation of the flocculation natural water does depend upon the settling depth and selection of appropriate settling depth for column analysis to provide the required correlation factor is of great importance.

Correlation factor is the safety factor (S.F.) obtained from the comparison of the results obtained from the column settling and the tube settler. This factor can be used directly for tube settler design. For example if a S.F. of 2 is accepted for practical design, this implies for the same efficiency to be achieved by the tube settler, the overflow rate obtained from the column settling tests which provides the same efficiency should be halved.

Table 5.7 contains all the correlation factors for various depths of settling columns.

A Least Squares Method was used to derive a general formula such as,

$$S.F. = 2.7014 - 0.0277 \times hc \qquad (5.17)$$

Correlation factor for the method is 90.84% and hc is the depth of the settling column. Figure. 5.12 shows the plot of equation (5.17).

Table 5.8 shows the comparison of the results of present study with some other past researches. YAO (1979) recommended that the safety factor

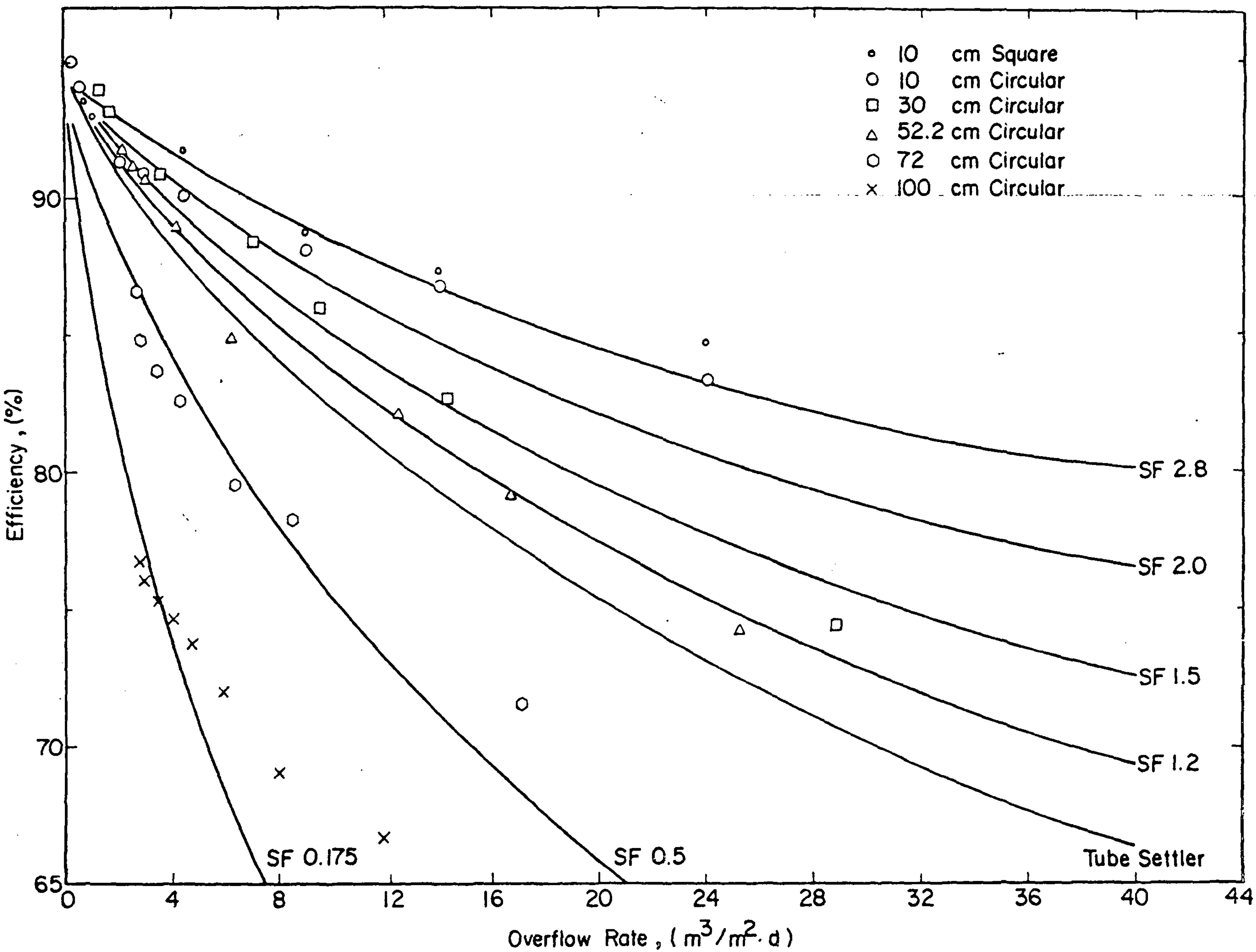


Fig 5.11 – Efficiency vs Overflow Rate from Column Settling Analysis

TABLE 5.7

Effect of Settling Depth Upon
Upon the Correlation Factor

Settling Depth (cm)	Correlation Factor
10.0	2.8
30.0	1.5
52.5	1.2
72.0	0.5
100.0	0.175

TABLE 5.8

Design Safety Factor for Overflow Rate Provided
by Column Settling to the Tube Settler System

Author	Nature of Water	Raw Water Turbidity (NTU)	Depth (cm)	Safety Factor
YAO (1979)	Natural Raw Water	100 - 280 (May-Sept)	78	2.0
		14 - 70 (Sept-Nov)	78	2.0
	Uncoagulated Synthetic Raw Water	100 - 280	78	2.0
PANNEER-SELVAM (1982)	Synthetic Flocculated Water	160 120 80	106 106 106	1.0 1.4 2.0
SOW (1983)	Natural Flocculated Water	25 - 30	10 25 30 52.5 72 100	2.8 2.0 1.5 1.2 0.5 0.175

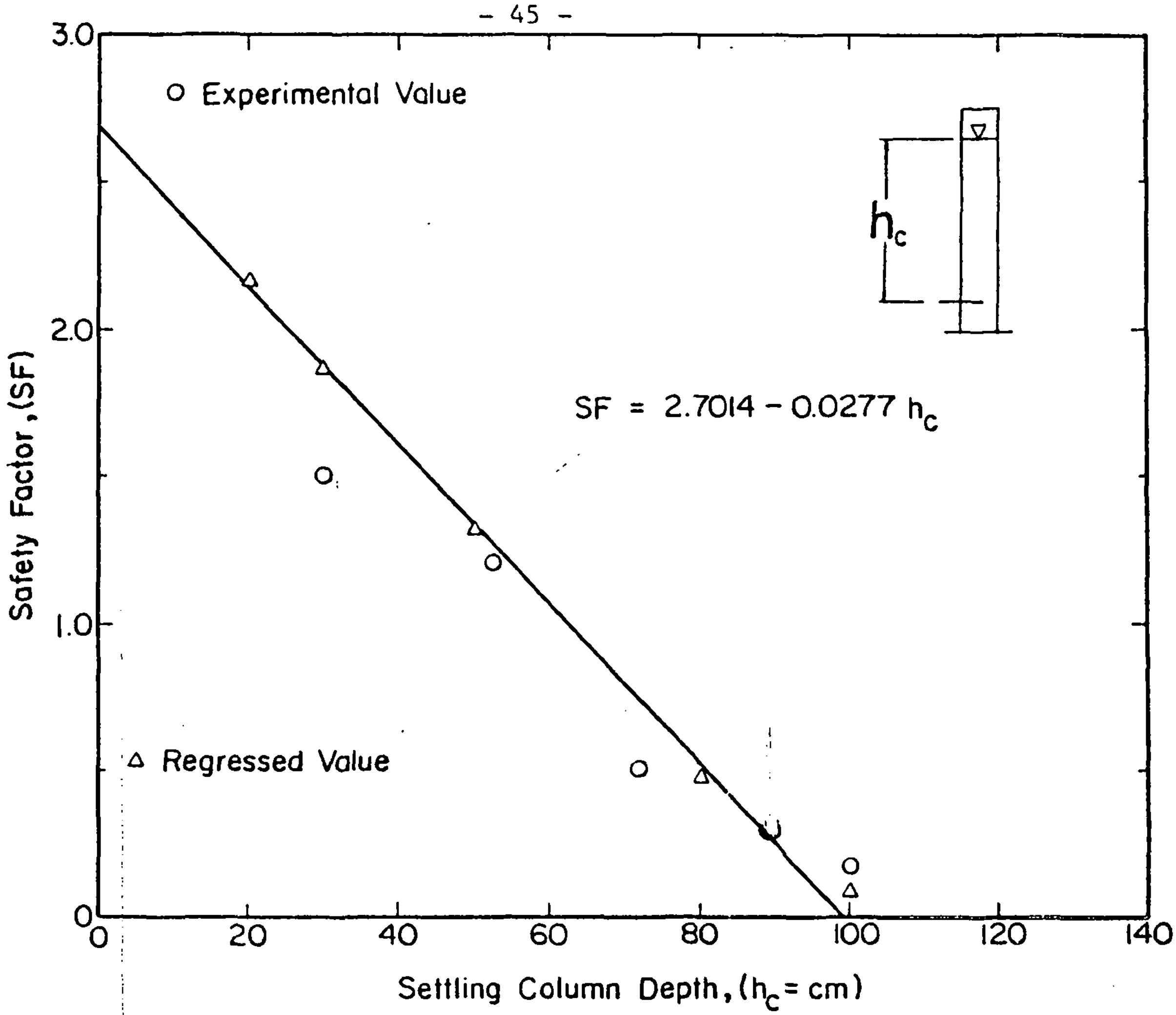


Fig. 5.12 - Safety Factor vs Settling Column Depth

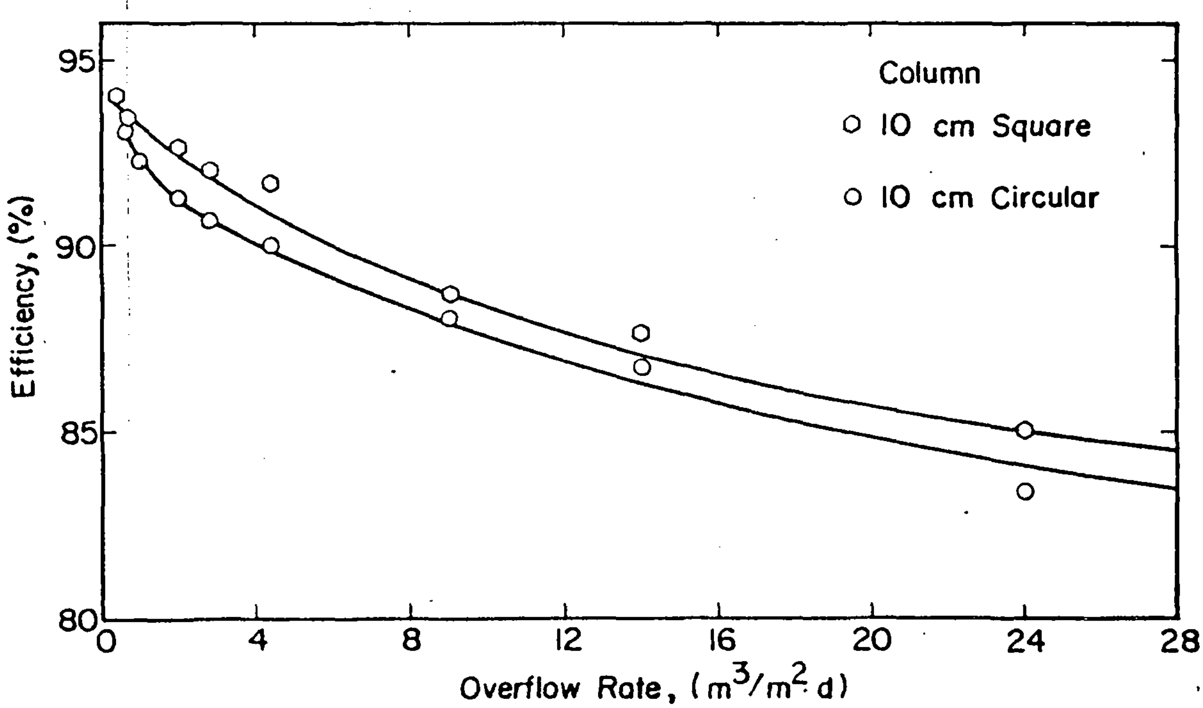


Fig. 5.13 - Efficiency vs Overflow Rate for Square & Circular Column

of 2 should be applied for natural unflocculated water and synthetic unflocculated water using settling column of 78 cm. PANNEERSELVAM (1982) also concluded that a safety factor of 2 was adequate for synthetic flocculated water using settling column of depth 106 cm. From this study, to provide a safety factor of 2, a column of settling depth of 25 cm can be employed.

Settling depth imparts a great influence upon the flocculation and clarification process of the natural flocculated water. Therefore, when selecting the settling column depth, one needs to realise that the overflow rate can be provided by various combinations of settling depth and detention time, for example:

Vsc = 1 m/h for hc = 1 cm and time = 1 h,

Vsc = 1 m/h for hc = 10 cm and time = 0.1 h = 6 min

Configuration of column does have effect upon the settling process. Fig. 5.13 shows the comparison of the results for settling column of 10 cm deep with circular and square type. Evidentally, square configuration does provides less residual current and as expected, it provides higher settling performance than that of the circular column. Thus, when specifying the design safety factor, one should also indicates the settling column depth and its configuration.

5.7 Practical Problem Encountered

From the experiment, it was observed that after 30 hours of continuous operation, the flocs start to clinge on to the tube surface and after 50 hours, the sludge begin to discharge to the effluent chamber and deteriorate the clarified water. In practice, several methods are available to overcome such circumstances. One method of removing this accumulation is by occasionally dropping the water level of the basin beneath the top of the tubes. The floc particles are then dislodged and fall to the bottom of the basin. This method of cleaning besets with practical problem since it is impossible in some cases to remove the basin from service in order to drop the level. Another cleaning technique involves the installation of a grid of diffused air headers beneath the tubes. To use this system, the influent is stopped and the air turned on and allowed to rise through the tubes, scrubbing any attached floc from the tubes. A quiescent period of 15-25 minutes follows before the basin is placed back in service. Such system demands a separate air supply system and thus discourage its wide application. Apart from the above mentioned methods, installation of a submerged water jet headers directly on top of the tubes appears to be the most attractive technique. In this system, sufficient turbulence is created on the edge of the tubes by the jet, thus loosen all the deposited material adhered to the top of the tubes.

5.8 Recommended Design Criteria and Numerical Example

To illustrate the applicability of the results obtained from the present study, the following design criteria and procedures are recommended and a numerical example is presented to aid in the understanding and use of the results.

Table 5.9 shows the recommended design values for overflow rate and flow velocity for various probable effluent qualities. If the effluent quality of 5 NTU is insisted, then the overflow rate of 8.0 m^3/m^2-d or flow velocity of 2.43 m^3/m^2-h can be used.

TABLE 5.9

Design Table Indicates the Recommended Values for Overflow Rate and Flow Velocity and Its Probable Effluent Turbidity

Raw Water Turbidity (NTU)	Alum Dose (mg/l)	Efficiency (%)	Overflow Rate (m^3/m^2 d)	Flow Velocity (m^3/m^2 h)	Probable Effluent Turbidity (NTU)
		90.00	2.38	0.72	2.5
		85.00	7.38	2.24	4.6
25 - 37	26	84.00	8.75	2.64	5.0
		80.00	12.75	3.87	6.1
		75.00	19.00	5.77	7.5
		90.00	7.00	2.13	4.6
		89.00	8.38	2.55	5.0
36 - 45	32	65.00	12.38	3.76	6.3
		80.00	18.50	5.43	7.9
		75.00	26.25	7.97	9.6
		90.00	1.75	0.53	2.2
		85.00	6.75	2.04	4.6
25 - 37	22	83.00	8.00	2.43	5.0
		80.00	12.13	3.68	6.7
		75.00	18.50	5.62	9.0

Table 5.10 and Table 5.11 are the design table which can be used to calculate the total number of tubes required for flow velocity at 2.43 m^3/m^2-h and 3.87 m^3/m^2-h respectively. Table 5.12 and Table 5.13 indicate the total plenum depths needed for various frequencies of desludging and plenum lengths.

EXAMPLE: A tube settler system is to be designed to serve a population of 10,000 people with per capita consumption of water amount to 100 ℓ/c·d. The influent turbidity is around 25 NTU to 40 NTU and it is preferable that the clarified water should not be more than 5 NTU.

TABLE 5.10

Design Table for The Total Number of Tubes Required

Flow Velocity = 2.43 m^3/m^2 h
Probable Effluent = 5.0 NTU
Raw Water Turbidity = 25 - 45 NTU
Temperature = 27 - 33 °C
Operation period = 24 Hours

Alum Dose = 22-32mg/l
Angle = 60°
Tube length = 0.9 m
Tube Size = 0.5cm x 0.5cm

	Per Capita Water Consumption (l/c.d)				
Population	50	100	150	200	250
10,000	3,440	6,860	10,290	13,720	17,150
20,000	6,860	13,720	20,580	27,440	34,300
30,000	10,290	20,570	30,870	41,160	51,440
40,000	13,720	27,440	41,160	54,870	68,590
50,000	17,150	34,300	51,440	68,590	85,740
60,000	20,580	41,160	61,730	82,310	102,880
70,000	24,020	48,020	72,020	96,030	120,030
80,000	27,440	54,870	82,310	109,740	137,180
90,000	30,870	61,730	92,600	123,460	154,330
100,000	34,300	68,590	102,890	137,180	171,470

TABLE 5.11

Design Table for The Total Number of Tubes Required

Flow Velocity = $3.87\ m^3/m^2\ h$
Probable Effluent = 6.1 - 6.7 NTU
Raw Water Turbidity = 25 - 45 NTU
Temperature = 27 - 33 °C
Operation period = 24 Hours

Alum Dose = 22-32mg/l
Angle = 60°
Tube length = 0.9 m
Tube Size = 0.5cm x 0.5cm

	Per Capita Water Consumption (l/c.d)				
Population	50	100	150	200	250
10,000	2,160	4,310	6,460	8,620	10,770
20,000	4,310	8,620	12,920	17,230	21,540
30,000	6,460	12,920	19,380	25,840	32,300
40,000	8,620	17,230	25,840	34,460	43,070
50,000	10,770	21,540	32,300	43,070	53,840
60,000	12,920	25,840	38,760	51,680	64,600
70,000	15,080	30,150	45,220	60,300	75,370
80,000	17,230	34,460	51,680	68,910	86,140
90,000	19,380	38,760	58,140	77,520	96,900
100,000	21,540	43,070	65,600	86,140	107,670

TABLE 5.12

Design Table for the Total Plenum Depths

Flow Velocity = 2.43 m^3/m^2 h
Probable Effluent = 5.0 NTU
Raw Water Turbidity = 25 - 45 NTU
Temperature = 27 - 33 °C
Tube Width (a) = 4 m
Alum Dose = 22-32mg/l
Angle = 60°
Tube length = 0.9 m
Tube Size = 0.5cm x 0.5cm

Frequency of Operation (day)	Symbol	Longitudinal Plenum Length (Lp (m)) 0.5	1.0	1.5	2.0	3.0
1	[1]Hx=0	0.70	0.43	0.34	0.30	0.26
	[2]Hx=Lp	1.18	0.62	0.44	0.35	0.26
2	Hx=0	1.23	0.70	0.52	0.44	0.35
	Hx=Lp	2.28	1.18	0.81	0.62	0.44
3	Hx=0	1.75	0.96	0.70	0.57	0.43
	Hx=Lp	3.38	1.73	1.11	0.90	0.63
4	Hx=0	2.28	1.23	0.88	0.70	0.52
	Hx=Lp	4.49	2.26	1.55	1.18	0.81

[1]Hx=0 (m) = total plenum depth at entrance
[2]Hx=Lp (m) = total plenum depth at a distance x = Lp

TABLE 5.13
Design Table for the Total Plenum Depths

Flow Velocity	= 3.87 m^3/m^2 h	Alum Dose	= 22-32mg/l
Probable Effluent	= 6.1-6.7 NTU	Angle	= 60°
Raw Water Turbidity	= 25 - 45 NTU	Tube length	= 0.9 m
Temperature	= 27 - 33 °C	Tube Size	= 0.5cm x 0.5cm
Tube Width (a)	= 4 m		

Frequency of Operation (day)	Symbol	Longitudinal Plenum Length (Lp (m))				
		0.5	1.0	1.5	2.0	3.0
1	[1]Hx=0	0.89	0.53	0.42	0.36	0.30
	[2]Hx=Lp	1.61	0.85	0.60	0.47	0.35
2	Hx=0	1.60	0.89	0.65	0.53	0.42
	Hx=Lp	3.14	1.62	1.11	0.76	0.51
3	Hx=0	2.31	1.25	0.89	0.71	0.53
	Hx=Lp	4.65	2.37	1.62	1.24	0.85
4	Hx=0	3.02	1.60	1.13	0.89	0.65
	Hx=Lp	6.17	3.13	2.12	1.62	1.10

[1]Hx=0 (m) = total plenum depth at entrance
[2]Hx=Lp (m) = total plenum depth at a distance x = Lp

SOLUTION: From Table 5.9, flow velocity of 2.43 m^3/m^2-h will provide an effluent quality of 5 NTU. For this flow velocity, Table 5.10 gives the total number of tubes required, i.e. 6,860 (tube dimensions: 5 cm x 5 cm x 90 cm).

Say, if daily desludging is feasible and a plenum length of 1 m can be allocated, then the total plenum depth of 1 m (see Table 5.12) is adequate with a safety factor of 38%.

VI ECONOMIC ANALYSIS

6.1 Introduction

Many developing countries are at present trying to achieve fast social and economic development with the problem of limited available resources. Since these resources are scarce and at any moment their availability is limited in the sense that if a resource is used for one purpose, it is denied to another which therefore will be forgone. Such situation demands the determination of design alternatives which could provide the desirable cost effective system. Economic analysis therefore can be used as a tool to assess the creditability of each alternative.

6.2 Need of Cost Estimation

Sedimentation is one of the most commonly used process in the field of water and wastewater treatment. It was estimated that about 1/3 of the total capital investment is spent on this unit operation, for this reason, economical alternatives should be considered in the modern water and wastewater treatment systems.

Many authors claimed that tube settler could provide same or even better performance than that of the conventional sedimentation tank with relatively low cost, therefore this section will be devoted to the cost estimation of both the systems and to compare their cost-effectiveness.

6.3 Design Assumptions

In designing the conventional sedimentation tank and the tube settler, the following assumptions will be used:

(1) Population served = 10,000
(2) Daily water demand = 150 ℓ/c·d
(3) Plant operation period = 24 h/d
(4) Check list presented in Table 6.1 is applicable
(5) For tube settler, 80% efficiency is acceptable
(6) Cost of form work includes nail, wood etc.
(7) Cost of equipments is not included
(8) Cost of excavation is not included
(9) Operation and maintenance costs are excluded
(10) Expected life-span for the sedimentation unit, tube settler and the plywood tube is 15 years, 15 years and 5 years, respectively.

$$\text{Plant capacity} = 10{,}000 \times 150/(24 \times 1{,}000)\ (m^3/h)$$
$$= 62.5\ m^3/h$$

TABLE 6.1 Check List (1982 - 1983 Bangkok's Market Price)

Item	Cost (Thai Baht)
Concrete	1,025 Baht/m^3
Form Work	25 Baht/m^2
Plywood (4 mm)	90 Baht/m^2
Steel	9 Baht/Kg

6.4 Design of Sedimentation Tank and Its Cost Estimation

The detention time for the clarifier at Bang Khen Water Treatment Plant is 113 minutes. GLUMRB Standards recommended that the detention time for suspended solid contact clarifier should be greater than or equal to 2 hours. Let choose the detention time of 2 hours for the design.

Detention time = 2 h
Horizontal velocity = 10 m/h
Volume of the tank = 62.5 x 2
= 125 m^3

Let the depth = 4 m + 1 m (free board)

Surface area of tank = 125/4
= 31.25 m^2

Depth x W x flow velocity = Plant capacity

4 x W x 10 = 62.5 m^3/h

W = 1.56 m^2

Say W = 1.6 m^2

Length of the tank = 31.25/1.6
= 19.53 m

Say L = 20 m

Actual surface area of the tank = 20 x 1.6 = 32 m , which is greater than 31.25 m^2, the design is acceptable.

Let the wall of the reinforcement concrete be 0.2 m thick,

Volume of concrete required = (20 x 0.2 x 5) x 2 + (1.6 x 0.2 x 5) x 2
+ (20 x 1.6 x 0.2)
= 49.6 m^3

Unit cost of concrete + labour = 1,025 Baht/m^3

Total cost of concrete + labour = 50,840 Baht

Steel reinforcement = 50 kg/m^3 of concrete

Total steel required	= 2,480 kg
Unit cost of steel + labour	= 9 Baht/kg
Total cost of steel + labour	= 22,320 Baht
Area required for form work	= (20 x 5) x 4 + (1.6 x 5) x 4
	= 432 m^2
Unit cost of form work + labour	= 25 Baht/m^2
Total cost of form work + labour	= 10,800 Baht
Total cost of sedimentation tank (excluding pipe, equipments)	= 50,840 + 22,320 + 10,800 (Baht)
	= 83,960 Baht
Amortized cost	= P(crf) (HARBOLD, 1980)

where crf is the capital recovery factor.

crf - 10% - 15 years	= 0.131474 (GITTINGER, 1979)
Amortized cost	= 83,960 x 0.131474
	= 11,039 Baht (say)
Contigency 10%	= 8,396 Baht
Final total cost	= 103,395 Baht

6.5 Design of Tube Settler and Its Cost Estimation

From the experimental result, for 80% efficiency the recommended flow rate is 3.87 m/h.

Plant capacity	= 62.5 m^3/h.
Flow velocity	= 3.87 m/h
Required tube settler area	= 62.5/3.87 (m^2)
	= 16.15 m^2

Let choose square tube of 5 cm x 5 cm x 90 cm and assuming 80 tubes per column,

No. of tube required	= $(16.15/25) \times (100)^2$
(see Table 5.11)	= 6,460
No. of column of tubes	= 6,460/80
	= 81 (say)
Actual total No. of tubes	= 80 x 81
	= 6,480 (acceptable)
Length of column	= 81 x 0.05 m

Let the inlet and the outlet chamber total to 1 m width, and the frequency of desludging is 1 day. Therefore, from Table 5.13 the plenum depth of 1 m is adequate.

Surface area occupied by the tube settler = 1.9 x 4.05
= 7.695 m^2

Volume of concrete = 4.05 x 0.2 x 5 + 4.05 x 0.2 x 4 + 0.5 x 0.2 x 4 x 2 + 0.5 x 0.2 x 5 x 2 + 0.5 x 0.2 x 4.05 x 2 + 4.05 x 1 x 0.2 + 4.05 x 0.9 x 0.2
= 11.44 m^3

Total cost of concrete + labour = 1025 x 11.4
= 11,726 Baht (say)

Total steel required = 572 kg

Total cost of steel + labour = 5,148 Baht (say)

Area required for form work = 4.05 x 5 x 2 + 4.05 x 4 x 2 + 0.5 x 5 x 4 + 0.5 x 4 x 2
= 87 m^2 (say)

Total cost of form work + labour = 2,175 Baht

Subtotal cost = 11,726 + 5,148 + 2,175
= 19,049 Baht

crf - 10% - 15 years = 0.131474

Amortized cost = 19,049 x 0.131474
= 2,505 (say)

Unit cost of plywood = 90 Baht/(2.5 m x 2.5 m x 4 mm)

Effective No. of tube = (2.5/0.05 x 2) x 2
in one sheet = 50

No. of sheet needed = 130

Total cost of plywood = 130 x 90
= 11,700 Baht

Let the design period be 15 years and the life-span of the plywood be 5 years. The rate of interest is 10% and the inflation rate is 13%, therefore according to THUESEN et al. (1977):

Present cost of plywood = 11,700 Baht

Cost of plywood in 5 years time
(at inflation rate of 13%) = 21,557 Baht

Present worth of plywood = 13,387 Baht
(at 10% interest rate)

Cost of plywood in 10 years time (at inflation rate of 13%)	=	35,147 Baht
Present worth of plywood (at 10% interest rate)	=	13,567 Baht
Total present worth of plywood	=	38,654 Baht
crf - 10% - 5 years	=	0.263797
Amortized cost	=	38,654 x 0.263797
	=	101,976 Baht (say)
Total cost of tube settler (excluding amortized cost)	=	57,703 Baht
Contigency 10%	=	5,770 Baht
Final total cost	=	76,175 Baht

6.6 Summary

From the cost estimation, it is clear that the tube settler system only required 1/4 of the land needed for the construction of the conventional sedimentation tank. As for the construction cost, the tube settler can provide a saving of 1/4 of the total cost involves in the construction of the conventional sedimentation.

VII CONCLUSIONS

Tube settler can play an important role in the modern water treatment plant. Its applicability in urban water supply can be validated by the following conclusions:

(1) From the jar test experiment, the optimum alum dose for raw water turbidity of 25-45 NTU was 28 mg/ℓ to 32 mg/ℓ. Addition of polyelectrolytes, whether they are cationic or anionic have no significant effect upon their settling performance.

(2) In Bang Khen Water Treatment Plant, the Authority has imposed a stringent criteria such that the clarified water should not exceed 5 NTU so as to ensure no overloading of the filter system. The tube settler used in the present study does in fact satisfy the above requirement. For raw water turbidity in the range of 25 NTU to 37 NTU and working under the optimum alum concentration, maximum overflow rate of 8.75 m^3/m^2-d can be used to provide effluent quality of equal or less than 5 NTU. For economic reasons, usually the "economic" alum dose is used, thus if the tube settler is performing at the 'economic' alum" dose and at 8 m^3/m^2-d, then it can provide a effluent satisfying the requirement of 5 NTU.

(3) If 80% efficiency is accepted for practical design, overflow rates of 12.75 m^3/m^2-d and 18.5 m^3/m^2-d for raw water turbidity of 25-37 NTU and 36-45 NTU can be used, respectively. But it is important to note that higher percent removal does not automatically implies the effluent could comply with the required standard.

(4) For practical application, the following formulations can be used to predict the overflow rate (Vsc) by specifying the required efficiency (E):

$$\ln E = 4.52993 - 0.01140 \times Vsc \quad \text{for 25-37 NTU}$$

$$\ln E = 4.55008 - 0.00873 \times Vsc \quad \text{for 36-45 NTU}$$

(5) The recommended overflow rate from this study is 8 m^3/m^2-d which is double the recommended overflow rate concluded by PANNEERSELVAM.

(6) Plenum forms an important component of tube settling system. From the sludge profile, it is clear that the point immediately below the tube is the most critical due to the fact that the sludge accumulated at it maximum rate.

(7) For practical plenum design, it is necessary to consider the height of the settled sludge operate at t hours and the critical plenum depth for certain flow velocity. If the tube settler has a plenum of length Lp (cm) and tube thickness of a (cm) and operate for t hours at velocity V (m^3/m^2-h), then the following equations can be used to calculate the total depth needed immediately below the tube and at entrance;

$Hx = 0\ (cm) = hs, x = 0 + hx = 0$

$Hx = Lp\ (cm) = hs, x = Lp + hx = Lp$

where Ho = total depth at the entrance

Hx = Lp = total depth immediately below the tube

hs, x = 0 = depth of settled sludge at entrance

hs, x = Lp = depth of settled sludge at distance x = Lp

hx = 0 = critical depth of plenum at entrance

hx = Lp = critical depth of plenum at distance x = Lp

Therefore,

$$Ho = 1.28499V^{0.63917}\ (t/8)(32/Lp)(a/33) + 14.92354V^{0.13574}$$

$$Hx = Lp = 2.57147V^{0.68808}\ (t/8)(32/Lp)(a/33) + 4.29316V^{0.57992}$$

(8) From the experiment, for 80% turbidity removal, the recommended flow velocity for raw water turbidity of 25-37 NTU and 36-45 NTU is 3.87 m^3/m^2-h and 5.43 m^3/m^2-h, respectively. To comply with the effluent requirement of 5 NTU working under optimum alum dose, then velocity of 2.67 m^3/m^2-h should be used for raw water turbidity of 25-37 NTU.

(9) From the experimental observation, it is recommended that submerged water jet system should be installed and daily jetting is necessary to prevent the sludge from adhering to the surface of the tubes.

(10) Column settling results indicate that the trend of overflow rate versus the percent turbidity removal ressemble very closely to those computed from the tube settler results. Thus column settling analysis could be used to provide correlation for the scale-up of the tube settler system.

(11) The following general formulation can be used to provide the require depth of the settling column for specified safety factor (S.F.),

$$S.F. = 2.7014 - 0.0277\ hc$$

where hc is the height of the settling column of circular type.

For safety factor of 2, the recommended depth of settling column of circular type is 25 cm.

(12) From the cost analysis, the cost of installing the tube settler system is 3/4 that of the conventional sedimentation system. Land requirement for the tube settler system is 1/4 that of the conventional one.

VIII RECOMMENDATION FOR FUTURE WORK

1. One of the most interesting applications now being evaluated is the use of steeply inclined tube settler directly in the aeration basin of an activated sludge plant. With proper design and allocation of the baffles, it appears possible to achieve activated sludge solids separation and return without a secondary clarifier structure, therefore the economic implications in secondary plant construction are indeed significant.

2. With the present knowledge about the characteristics of the raw water in Bang Khen Water Treatment Plant and also the operation parameters of the tube settler system. Further work can be pursued by installing the tube into the contact solid clarifier and to evaluate the creditibility of upgrading the overloaded clarifier.

3. From this research, it was observed that sludge deposited on the surface of the tubes after 30 hours of continuous operation. Therefore, it is recommended that submerged water headers should be installed directly above the tubes so as to create sufficient turbulence to dislodge the deposited sludge. As for the frequency of cleaning, daily jetting is necessary but YAO (1971) recommended that weekly cleaning is sufficient, eventhough he understood that weekly cleaning does momentarily deteriorate the effluent quality while cleaning on daily basis does not substantially deteriorate the effluent quality. To justify the above recommendation, further work can be pursued to determine the design criteria for the submerged water jet headers and also to find out the frequency of cleaning that could provide the best result.

REFERENCES

ADAM, C.E., FORD, D.L. and ECKENFELDER, W.W. (1981), Development of Design and Operation Criteria for Wastewater Treatment, C.B.I. Publication, 91.

AMIN, M.M. (1974), Performance of Tube Settlers in Clarification of Turbid Tropical Surface Waters, Master's Thesis No. 636, Asian Institute of Technology, Bangkok, Thailand.

ARIES, R.S. (1955), Chemical Engineering Cost Estimation, McGraw-Hill Book Co.

BARNES, D. et al. (1978), Chemistry and Unit Operations in Sewage Treatment, Applied Science Publications Limited, London, 115.

BEACH, W.A. (1972), Fundamentals of Tube Settler Design, 27th Ind. Waste Conf. Purdue Univ. Engg. Extn. Series No. 141, 67.

BINH, N.C. (1975), Optimization of the Inclined Tube Settlers and Anthracite-Sand Filter, Master's Thesis No. 834, Asian Institute of Technology, Bangkok, Thailand.

BRAHAM, W.L., MATHERNE, J.L. and KELLER, A.G. (1956), Clarification, Sedimentation and Thickening Equipment, A Patent Review, Bulletin No. 54, Eng. Experimental Station, Louisiana State Univ. (Baton, Rouge, La).

CAMP, T.R. (1946), Sedimentation and the Design of Settling Tank, Trans. ASCE., 3, 895.

CAMP, T.R. (1953), Studies of Sedimentation Basin Design, Sew. Ind. Waste, 25, 1.

CHEN, Y.R. (1979), Design Criteria for Inclined Tube Settlers, Master's Thesis No. EV-79-29, Asian Institute of Technology, Bangkok, Thailand.

CULP, G.L., et al. (1968), High Rate Sedimentation in Water Works, J. AWWA. 60, 691.

CULP, G.L., HSIUNG, K.Y. and CONLEY, W.R. (1969), Tube Clarification Process, Operating Experiences, J. Sanit. Eng. Div. Proc. ASCE. 95, 829.

CULP, G.L. and CULP, R.L. (1970), New Concepts in Water Purification, Van. Nostrand Reinhold.

DANIEL, C. and WOOD, F.S. (1971), Fitting Equations to Data, Computer Analysis of Multifactor Data for Scientists and Engineers, Wiley-Interscience Publication.

DICK, R.I. (1970), Tube Clarification Process, Operating Experiences, J. Sanit. Eng. Div., ASCE, 96, 1009.

DRESSER, H.G. (1951), Trays, Nearly Tripple Settling Tank Capacity, Eng. News Record, V147, No. 29, 32.

ECKENFILDER, W.W. (1966), Industrial Water Pollution and Control, McGraw-Hill Book Co., 28.

FAIR, G.M. et al. (1968), Water Purification and Wastewater Treatment and Disposal-Volume 2, John Wiley and Sons Inc., New York.

FISHCHERSTROM, C.N.H. (1955), Sedimentation in Rectangular Basin, Proc. ASCE., J. Sanit. Eng. Div.

FREI, J.K. (1941), Multiple-Tray Clarification at a Modern Treatment Plant, J. Sew. Eng. Div., 12, 423.

GITTINGER, J.P. (1979), Compounding and Discounting Tables for Project Evaluation, EDI, Teaching Materials Series Number 1, Johns Hopkins University Press, London.

HANSEN, S.P. et al. (1967), Applying Shallow Depth Sedimentation Theory, J. AWWA., 1134.

HANSEN, S.P. et al. (1969), Some Recent Advances in Water Treatment Technology, Chemical Engineering Progress Symposium Series, 65, 97, 207.

HARBOLD, H.S. (1980), Sanitary Engineering Problems and Calculations for the Professional Engineers, Ann Arbor Science, 227.

HAZEN, A. (1904), On Sedimentation, Trans. ASCE., 53, 45.

HAZEN, S.P. and CULP, G.L. (1967), Applying Shallow Depth Sedimentation Theory, J. AWWA, 59, 1134.

HERBERT, E.H., Jr. (1981), Water Clarification Processes, Practical Design and Evaluation, Van Nostrand, Env. Eng. Series, 146.

HOPKINS, J. (1979), Compounding and Discounting Tables for Project Evaluation, A. World Bank Publication, EDI Teaching Materials Series, Number 1.

HUDSON, H.E. and WAGNER, E.G. (1981), Conduct and Uses of Jar Tests, J. AWWA., V73, No. 4, 218.

LIENGCHARERNSIT, W. (1975), Use of Bamboos and Corrugated Asbestos as Local Materials for Tube Settler, Master's Thesis, Asian Institute of Technology, Bangkok, Thailand.

MORAN, W.D. and CHEYER, T.F. (1975), Bang Khen-Bangkok's Response to a Critical Water Shortage, J. AWWA., V 67, No. 6, 302.

MOSTELLER, F. and TUKEY, J.W. (1977), Data Analysis and Regression, 2nd Edition, Addison-Wesley Publishing Company.

O'CONNOR, J.T. (1975), Environmental Engineering Unit Operations and Unit Processes, Laboratory Manual, 2nd Edition, Association of Environmental Engineering Professors, University of Texas.

PANNEERSELVAM, K.N. (1982), Use of Tube Settlers for Tropical Surface Water Treatment, Master's Thesis, Asian Institute of Technology, Bangkok, Thailand.

PEURIFOY, R.L. (1975), Estimating Construction Costs, 3rd Edition, McGraw-Hill Inc.

RICH, L.G. (1973), Environmental Systems Engineering, McGraw-Hill Book Co., 336.

SCHMITT, E.A. and VOIGT, O.D. (1949), Two Storey Flocculation Sedimentation Basins for the Washington Aqueduct, J. AWWA., V. 41, No. 9, 837.

SLECHTA, A.F. and CONLEY, W.R., (19), Recent Experience in Plant Scale Application of the Settling Tube Concept, J. WPCF., 43, 1724.

TARIQ, M.N. (1976), A Laboratory Study on Tube Settling, Ins. of Public Health Eng. and Research, Univ. of Eng. and Technology, Pakistan.

TCHOBANOGLOUS, G. (1979), Wastewater Engineering : Treatment Disposal and Reuse, Metcalf and Eddy Inc., McGraw-Hill Pub., 201.

THANH, N.C., CHEN, Y.R. and LOHANI, B.N. (1979), Practical Design Criteria for Inclined Tube Settlers, 2nd Regional Conf. on Water Supply, Taipei, Environmental Eng. Div., Asian Institute of Technology, Bangkok, Thailand.

THUESEN, H.G. (1977), Engineering Economic, Prentice Hall Inc., 123.

VAN VLIET, B.M. (1977), The Efficiency of Inclined Tube and Plate Modules in a High Rate Clarification Process, Water Research, V 11.

VASANADILOKLERT, P. (1978), Use of Inclined Tube-Settlers in Water Treatment System, Master's Thesis No. 1403, Asian Institute of Technology, Bangkok, Thailand.

WALPOLE, R.E. and MYERS, R.H. (1978), Probability and Statistics for Engineers and Scientists, 2nd Edition, Collier Macmillan International Editions, 280.

WILLIS, R.M. (1978), Tubular Settlers - A Technical Review, J. AWWA., 331.

YAO, K.M. (1970), Theoretical Study of High Rate Sedimentation, J. Wat. Pollut. Cont. Fed., 72, 218.

YAO, K.M. (1973), Design of High Rate Settlers, J. Env. Eng. Div., Proc. ASCE, 621.

YAO, K.M. (1975), Extended Plain Sedimentation, Proc. ASCE., Env. Eng., Div. 101, 413.

YAO, K.M. (1976), Theoretical Study of High Rate Sedimentation, J. WPCF, 72, 218.

YAO, K.M. (1979), Colume Settling Test and Tube Settling, J. AWWA, 71, 109.

"Bang Khen Water Treatment Plant", Jan. 1981, Metropolitan Water Works Authority, Bangkok, Thailand.

"Drinking Water and Sanitation, 1981-1990, A Way To Health", WHO, Switzerland.

"The Application of Inclined Tubes or Plates to Sedimentation Tanks in Wastewater Treatment", 1975, Water Research Centre, No. 68.

"Tube Settlers Up Clarifier Throughput", April 1972, Env. Sc. and Technology, V 6, 312.

APPENDIX A

JAR TEST EXPERIMENTATION

TABLE A1-1

Determination of Optimum Alum Concentration

Raw Water Turbidity : 25 NTU
Optimum Alum Concentration : 28 mg/l

Jar Number		1	2	3	4	5	6
Alum Concentration (mg/l))		14.0	18.0	22.0	26.0	28.0	30.0
Residual Turbidity (NTU)	10 min Settling	7.4	5.1	3.9	3.3	3.0	3.1
	30 min Settling	6.0	4.6	3.1	2.6	2.2	2.3

TABLE A1-2

Determination of Optimum Alum Concentration

Raw Water Turbidity : 40 NTU
Optimum Alum Concentration : 28 mg/l is sufficient

Jar Number	1	2	3	4	5	6
Alum Concentration (mg/l)	14.0	18.0	22.0	26.0	28.0	30.0
Residual Turbidity (NTU)	2.0	1.2	1.1	0.86	0.82	0.70

TABLE A1-3

Determination of Optimum Alum Concentration

Raw Water Turbidity : 56 NTU
Optimum Alum Concentration : 34 mg/l

Jar Number	1	2	3	4	5	6
Alum Concentration (mg/l)	18.0	22.0	28.0	32.0	36.0	40.0
Residual Turbidity (NTU)	7.5	6.0	4.5	3.3	3.3	3.6

TABLE A2-1

To Determine the Effect of Cationic Polyelectrolyte Upon the Residual Turbidity

Raw Water Turbidity : 25 NTU
Optimum Alum Concentration : 28 mg/l
Polyelectrolyte : CAT-FLOC T

Jar Number	1	2	3	4	5	6	7	8
Polyelectrolyte (mg/l)	.008	.006	.004	.002	.0015	.0010	.0005	.0003
Residual Turbidity (NTU)	6.9	4.6	2.8	2.6	2.8	3.0	3.2	3.3

TABLE A2-2

To Determine the Effect of Anionic Polyelectrolyte Upon the Residual Turbidity

Raw Water Turbidity : 30 NTU
Polyelectrolyte : SUPERFLOC

Jar Number	1	2	3	4	5	6
Alum Concentration (mg/l)	14.0	16.0	18.0	20.0	22.0	24.0
Residual Turbidity (NTU)	7.1	6.0	5.6	4.6	4.3	3.1

Jar Number	1	2	3	4	5	6
Alum Concentration (mg/l)	20.0	20.0	20.0	20.0	20.0	20.0
Polyelectrolyte (mg/l)	.000	.050	.060	.065	.070	.080
Residual Turbidity (NTU)	5.7	5.5	4.9	4.7	5.1	5.1

Jar Number	1	2	3	4	5	6
Alum Concentration (mg/l)	22.0	22.0	22.0	22.0	22.0	22.0
Polyelectrolyte (mg/l)	.000	.050	.060	.065	.070	.080
Residual Turbidity (NTU)	4.5	4.5	4.2	4.5	4.6	4.5

Table A3-1

To Evaluate the Applicability of PAC on Coagulation and Flocculation Process

Raw Water Turbidity : 31 NTU

Jar Number	1	2	3	4	5	6
Alum Concentration (mg/l)	14.0	16.0	18.0	20.0	22.0	24.0
Residual Turbidity (NTU)	6.7	5.6	4.8	3.6	3.4	3.0
PAC Concentration (mg/l)	6.0	8.0	10.0	12.0	14.0	16.0
Residual Turbidity (NTU)	8.1	5.8	4.2	3.5	3.1	2.7

* PAC = Poly Aluminum Chloride

APPENDIX B

TUBE SETTLER PERFORMANCE

TABLE B1-1

Performance of the inclined Tube Settler for Raw Water Turbidity of 25 NTU to 37 NTU

Flow : 2 l/min , Average Effluent Turbidity: 2.8 NTU
Flow Velocity : 0.8 m/h Average Efficiency : 89.63 %
Overflow Rate : 2.68 m^3/m^2 d Alum Concentration : 28 mg/l

Operating Time (h)	Raw Water Turbidity (NTU)	Flocculated Water (NTU)	Effluent Turbidity (NTU)	Efficiency %	Temperature °C
1	29	19	8.5	70.69	32
2	29	18	7.5	74.14	32
3	29	17	6.7	76.90	32
4	29	18	5.5	81.04	33
5	29	18	5.0	82.14	33
6	33	17	4.2	87.27	33
7	35	16	3.8	89.14	30
8	27	18	3.4	87.41	30
9	26	16	3.0	88.50	30
10	28	17	3.0	89.29	30
11	28	17	2.7	90.36	30
12	27	13	2.6	90.37	30

TABLE B1-2

Performance of the Inclined Tube Settler for Raw Water Turbidity of 25 NTU to 37 NTU

Flow : 5 l/min
Flow Velocity : 2.0 m/h
Overflow Rate : 6.70 m^3/m^2 d
Average Effluent Turbidity: 4.5 NTU
Average Efficiency : 86.72 %
Alum Concentration : 28 mg/l

Operating Time (h)	Raw Water Turbidity (NTU)	Flocculated Water (NTU)	Effluent Turbidity (NTU)	Efficiency %	Temperature °C
1	32	17	3.4	89.39	28
2	32	18	7.3	77.19	28
3	29	20	6.3	78.28	28
4	37	21	5.8	84.32	28
5	33	20	5.1	84.55	29
6	36	21	4.8	86.67	30
7	36	21	5.0	86.11	31
8	32	18	4.1	87.19	32
9	37	17	4.3	88.38	33
10	31	17	3.9	87.42	33

TABLE B1-3

Performance of the Inclined Tube Settler for Raw Water Turbidity of 25 NTU to 37 NTU

Flow : 10 l/min
Flow Velocity : 4.0 m/h
Overflow Rate : 13.38 m^3/m^2 d
Average Effluent Turbidity : 6.5 NTU
Average Efficiency : 79.24 %
Alum Concentration : 28 mg/l

Operating Time (h)	Raw Water Turbidity (NTU)	Flocculated Water (NTU)	Effluent Turbidity (NTU)	Efficiency %	Temperature °C
1	31	22	4.0	87.10	30
2	31	22	6.6	78.76	29
3	29	24	7.2	75.17	29
4	25	20	4.2	83.20	29
5	27	21	5.6	79.26	29
6	33	23	7.8	76.36	28
7	31	24	8.2	73.55	28
8	34	23	8.5	75.00	27
9	30	22	4.2	86.00	27
10	32	23	4.5	85.94	27

TABLE B1-4

Performance of the Inclined Tube Settler for Raw Water Turbidity of 25 NTU to 37 NTU

Flow : 15 l/min
Flow Velocity : 6.0 m/h
Overflow Rate : 20.07 m^3/m^2 d
Average Effluent Turbidity: 7.3 NTU
Average Efficiency : 76.75 %
Alum Concentration : 28 mg/l

Operating Time (h)	Raw Water Turbidity (NTU)	Flocculated Water (NTU)	Effluent Turbidity (NTU)	Efficiency %	Temperature °C
1	33	27	4.9	85.15	27
2	33	30	12.0	63.64	27
3	29	19	11.0	62.07	28
4	29	19.5	7.2	75.17	28
5	32	20	7.5	76.56	28
6	37	22	7.0	81.06	29
7	30	21	7.6	74.67	29
8	32	28	7.2	77.50	29
9	29	26	7.1	75.52	30

TABLE B1-5

Performance of the Inclined Tube Settler for Raw Water Turbidity of 25 NTU to 37 NTU

Flow : 20 l/min　　Average Effluent Turbidity: 8.9 NTU
Flow Velocity : 8.0 m/h　　Average Efficiency : 68.33 %
Overflow Rate : 26.76 m^3/m^2 d　　Alum Concentration : 28 mg/l

Operating Time (h)	Raw Water Turbidity (NTU)	Flocculated Water (NTU)	Effluent Turbidity (NTU)	Efficiency %	Temperature °C
1	27	13	7.2	73.33	30
2	26	21	7.1	72.70	30
3	28	19	8.9	68.21	30
4	27	25	8.7	67.78	30
5	30	26	9.0	70.00	30
6	28	20	8.9	68.21	29
7	28	20	9.0	68.86	29
8	27	25	8.8	67.41	28
9	28	23	9.0	67.86	28

TABLE B2-1
Performance of the Tube Settler at Economical Alum dose

Flow : 6.0 l/min
Flow Velocity : 2.4 m/h
Overflow Rate : 8.03 m^3/m^2 d

Average Effluent Turbidity: 4.85 NTU
Average Efficiency : 87.19 %
Alum Concentration : 22 mg/l

Operating Time (h)	Raw Water Turbidity (NTU)	Flocculated Water (NTU)	Effluent Turbidity (NTU)	Efficiency %	Temperature °C
1	35	15	5.5	84.29	30
2	34	16	6.7	80.29	30
3	32	16	6.7	79.06	31
4	38	19	5.8	84.74	31
5	38	14	5.1	86.58	32
6	36	14	4.2	88.33	32
7	36	17	4.6	87.22	32
8	37	22	5.0	86.49	32
9	37	23	4.7	87.30	32
10	36	21	4.6	87.22	31

TABLE B2-2

Performance of the Tube Settler at Economical Alum dose

Flow : 8.0 l/min Average Effluent Turbidity: 6.40 NTU
Flow Velocity : 3.2 m/h Average Efficiency : 81.45 %
Overflow Rate : 10.70 m^3/m^2 d Alum Concentration : 22 mg/l

Operating Time (h)	Raw Water Turbidity (NTU)	Flocculated Water (NTU)	Effluent Turbidity (NTU)	Efficiency %	Temperature °C
1	37	27	6.4	82.70	30
2	36	25	6.6	81.67	31
3	37.5	24	6.8	81.87	31
4	33	29	7.5	77.27	31
5	35	31	7.1	79.71	32
6	34	29	7.5	77.94	32
7	34	26	6.6	80.43	32
8	35	27	6.2	82.41	33
9	34	25	6.3	81.50	33

TABLE B2-3
Performance of the Tube Settler at Economical Alum dose

Flow : 12.0 l/min
Flow Velocity : 4.8 m/h
Overflow Rate : 16.06 m^3/m^2 d

Average Effluent Turbidity: 8.20 NTU
Average Efficiency : 76.69 %
Alum Concentration : 22 mg/l

Operating Time (h)	Raw Water Turbidity (NTU)	Flocculated Water (NTU)	Effluent Turbidity (NTU)	Efficiency %	Temperature °C
1	35	20	7.2	79.43	31
2	34	22	9.0	73.53	31
3	36	25	9.2	74.44	30
4	35	18	8.9	74.57	30
5	34	23	8.7	74.41	30
6	35	20	8.3	76.21	30
7	36	29	8.2	77.22	29
8	35	23	8.2	76.57	29

TABLE B3-1

Performance of the Inclined Tube Settler for Raw Water Turbidity of 36 NTU to 45 NTU

Flow : 8.0 l/min
Flow Velocity : 3.2 m/h
Overflow Rate : 10.70 m^3/m^2 d

Average Effluent Turbidity: 5.8 NTU
Average Efficiency : 85.78 %
Alum Concentration : 32 mg/l

Operating Time (h)	Raw Water Turbidity (NTU)	Flocculated Water (NTU)	Effluent Turbidity (NTU)	Efficiency %	Temperature °C
0	37	26	7.0	81.08	33
1	43	28	5.4	87.44	33
2	41	29	5.6	86.34	33
3	60	28	5.0	91.67	32
4	41	27	5.4	86.83	32
5	38	29	5.5	85.53	31
6	37	30	5.0	86.49	31
7	39	29	6.0	84.62	30
8	42	28	5.5	86.91	30
9	38	28	6.2	83.68	29
10	38	27	6.0	84.21	29
11	39	26	6.1	84.36	28
12	40	29	6.0	85.00	27
13	42	29	6.3	85.00	27
14	45	25	6.0	86.67	27
15	40	29	6.2	84.50	26
16	36	24	6.1	83.06	28
17	40	29	6.0	85.00	29
18	40	23	6.0	85.00	29
19	41	24	5.2	87.32	30
20	43	28	6.0	86.05	30
21	42	20	6.0	85.71	30

TABLE B3-2
Performance of the Inclined Tube Settler for Raw Water Turbidity of 36 NTU to 45 NTU

Flow : 15.0 l/min Average Effluent Turbidity: 7.7 NTU
Flow Velocity : 6.0 m/h Average Efficiency : 80.36 %
Overflow Rate : 20.07 m^3/m^2 d Alum Concentration : 32 mg/l

Operating Time (h)	Raw Water Turbidity (NTU)	Flocculated Water (NTU)	Effluent Turbidity (NTU)	Efficiency %	Temperatur °C
0	38	28	19.0	50.00	27
1	37	29	9.0	75.68	27
2	40	29	7.5	81.25	28
3	36	21	7.3	79.72	28
4	45	28	7.0	84.44	29
5	40	27	7.1	82.25	29
6	39	26	7.2	81.54	29
7	35	29	7.0	80.00	30
8	40	29	8.0	80.00	30
9	39	27	9.0	76.92	31
10	40	28	8.0	80.00	31

TABLE B3-3

Performance of the Inclined Tube Settler for Raw Water Turbidity of 36 NTU to 45 NTU

Flow :20.0 l/min Average Effluent Turbidity: 9.8 NTU
Flow Velocity : 8.0 m/h Average Efficiency : 74.41 %
Overflow Rate :26.76 m^3/m^2 d Alum Concentration : 32 mg/l

Operating Time (h)	Raw Water Turbidity (NTU)	Flocculated Water (NTU)	Effluent Turbidity (NTU)	Efficiency %	Temperature °C
0	41	25	12.5	69.51	32
1	37	29	10.0	72.97	32
2	38	28	9.5	75.00	32
3	39	27	9.5	75.64	33
4	39	26	9.0	76.92	33
5	39	28	10.0	74.36	33
6	39	28	10.0	74.36	33
7	38	27	10.0	73.68	32
8	38	26	10.5	72.37	32

TABLE B4-1

Performance of the Inclined Tube Settler at Different Overflow Rate and at Different Alum Concentration

Temperature: 27-33 °C

Raw Water (NTU)	Alum Dose (mg/l)	Overflow Rate (m^3/m^2 d)	Efficiency (%)	Effluent Turbidity (NTU)
25-37	22	8.03 10.70 16.06	87.19 81.45 76.69	4.85 6.40 8.20
25-37	28	2.68 6.70 13.38 20.07 26.76	89.63 86.72 79.24 76.75 68.33	2.80 4.50 6.50 7.30 8.90
36-45	32	10.70 20.07 26.76	85.78 80.36 74.41	5.80 7.70 9.80

TABLE B5-1

LEAST SQUARES METHODS OF ANALYSIS

Regression of Vsc Vs % Turbidity Removal for Turbidity of 25-37 NTU

	y'	y=ln y'	y^2	x	x^2	xy
	89.63	4.4957	20.2113	2.68	7.1824	12.0485
	86.72	4.4627	19.9157	6.70	44.8900	29.9001
	79.24	4.3725	19.1188	13.38	179.0244	58.5041
	68.33	4.2244	17.8456	26.76	716.0976	113.0049
Sum		17.5553	77.0913	49.52	947.1944	213.4976

Xav = 12.3800
Yav = 4.3888
B1 = -0.01140
Bo = 4.52993

Equation: ln E = 4.52993 - 0.01140 x Vsc

r = 0.99147
r^2 = 98.30 %

TABLE B5-2

LEAST SQUARES METHODS OF ANALYSIS

Regression of Vsc Vs % Turbidity Removal for Turbidity of 36-45 NTU

	y'	y=ln y'	y^2	x	x^2	xy
	85.78	4.4518	19.8184	10.70	114.49	47.63411
	80.36	4.3865	19.2415	20.07	402.8049	88.03740
	74.41	4.3096	18.5726	26.76	716.0976	113.3246
Sum		13.1479	57.6325	57.53	1233.392	250.99613

Xav = 19.1767
Yav = 4.38263
B1 = -0.008732
Bo = 4.55008

Equation: ln E = 4.55008 - 0.00873 x Vsc

r =0.9882
r^2 = 97.65 %

TABLE B6-1

Performance of the Inclined Tube Settler at Different Flow Velocity and at Different Alum Concentration

Temperature: 27-33 °C

Raw Water (NTU)	Alum Dose (mg/l)	Flow Velocity (m^3/m^2 h)	Efficiency (%)	Effluent Turbidity (NTU)
25-37	22	2.40	87.19	4.85
		3.20	81.45	6.40
		4.80	76.69	8.20
25-37	28	0.80	89.63	2.80
		2.00	86.72	4.50
		4.00	79.24	6.50
		6.00	76.75	7.30
		8.00	68.33	8.90
36-45	32	3.20	85.78	5.80
		6.00	80.36	7.70
		8.00	74.41	9.80

APPENDIX C

COLUMN SETTLING ANALYSIS

TABLE C1-1

Column Settling Analysis

Type of Column : Square
Settling Depth : 10 cm
Correlation Factor : 2.8

Raw Water Turbidity : 30 NTU
Alum Concentration : 28 mg/l

Time (h)	Effective height (cm)	Effluent Turbidity (NTU)	% Turbidity Removal	Overflow Rate (m/d)
0.10	10.0	4.6	84.67	24.00
0.17	9.7	3.8	87.33	13.90
0.25	9.4	3.4	88.67	9.02
0.50	9.1	2.5	91.67	4.37
0.75	8.8	2.4	92.00	2.82
1.00	8.5	2.3	92.33	2.04
2.00	8.2	2.1	93.00	0.98
3.00	7.9	1.95	93.50	0.63
4.00	7.6	1.9	93.67	0.46
5.00	7.3	1.8	94.00	0.35

TABLE C1-2

Column Settling Analysis

Type of Column : Circular
Settling Depth : 10 cm
Correlation Factor : 2.8

Raw Water Turbidity : 30 NTU
Alum Concentration : 28 mg/l

Time (h)	Effective height (cm)	Effluent Turbidity (NTU)	% Turbidity Removal	Overflow Rate (m/d)
0.10	10.0	5.0	83.33	24.00
0.17	9.7	4.0	86.67	13.90
0.25	9.4	3.6	88.00	9.02
0.50	9.1	3.0	90.00	4.37
0.75	8.8	2.8	90.67	2.82
1.00	8.5	2.6	91.33	2.04
2.00	8.2	2.3	92.33	0.98
3.00	7.9	2.1	93.00	0.63
4.00	7.6	1.7	94.33	0.46
5.00	7.3	1.5	95.00	0.35

TABLE C1-3

Column Settling Analysis

Type of Column : Circular
Settling Depth : 30 cm
Correlation Factor : 1.5

Raw Water Turbidity : 43 NTU
Alum Concentration : 28 mg/l

Time (h)	Effective height (cm)	Effluent Turbidity (NTU)	% Turbidity Removal	Overflow Rate (m/d)
0.25	30.0	11.0	74.49	28.80
0.50	29.7	7.5	82.56	14.26
0.75	29.4	6.0	86.05	9.41
1.00	29.1	5.0	89.77	6.98
2.00	28.8	3.9	91.86	3.46
3.00	28.5	3.3	92.79	2.28
4.00	28.2	2.95	93.14	1.69
5.00	27.9	2.6	93.95	1.34

TABLE C1-4

Column Settling Analysis

Type of Column : Circular
Settling Depth : 52.5 cm
Correlation Factor : 1.2

Raw Water Turbidity : 33 NTU
Alum Concentration : 28 mg/l

Time (h)	Effective height (cm)	Effluent Turbidity (NTU)	% Turbidity Removal	Overflow Rate (m/d)
0.50	52.5	8.5	74.24	25.20
0.75	52.2	6.9	79.10	16.70
1.00	51.9	5.9	82.12	12.46
2.00	51.6	5.0	84.85	6.19
3.00	51.3	4.0	87.88	4.10
4.00	51.0	3.1	90.61	3.06
5.00	50.7	2.9	91.21	2.43
6.00	50.4	2.7	91.82	2.02
7.00	50.1	2.0	93.94	1.72
8.00	49.8	1.7	94.85	1.49
9.00	49.5	1.6	95.15	1.32

TABLE C1-5

Column Settling Analysis

Type of Column : Circular
Settling Depth : 72.0 cm
Correlation Factor : 0.5

Raw Water Turbidity : 46 NTU
Alum Concentration : 28 mg/l

Time (h)	Effective height (cm)	Effluent Turbidity (NTU)	% Turbidity Removal	Overflow Rate (m/d)
0.70	71.7	16.0	65.79	24.58
1.00	71.4	13.0	71.74	17.14
2.00	71.1	10.0	66.67	8.53
2.70	70.8	9.5	68.33	6.29
4.00	70.5	8.0	73.33	4.23
5.00	70.2	7.5	75.00	3.37
6.00	69.9	7.0	76.67	2.80
7.33	69.6	6.0	80.00	2.78

TABLE C1-6

Column Settling Analysis

Type of Column : Circular
Settling Depth : 100 cm
Correlation Factor : 0.175

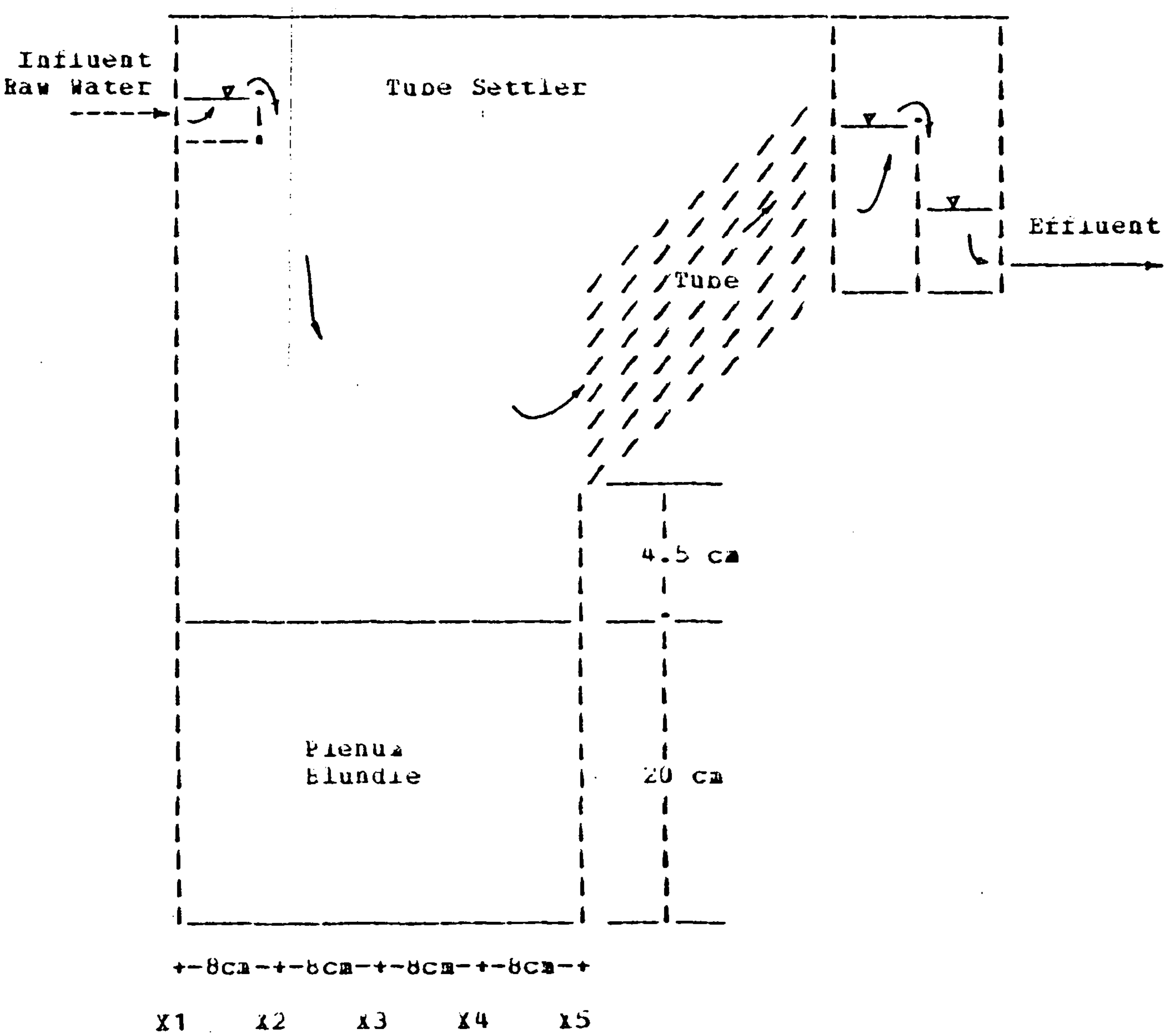
Raw Water Turbidity : 30 NTU
Alum Concentration : 28 mg/l

Time (h)	Effective height (cm)	Effluent Turbidity (NTU)	% Turbidity Removal	Overflow Rate (m/d)
1.00	99.7	12.0	60.00	23.93
2.00	99.4	10.0	66.67	11.93
3.00	99.1	9.3	69.00	7.93
4.00	98.8	8.4	72.00	5.93
5.00	98.5	7.9	73.66	4.73
6.00	98.2	7.6	74.66	3.93
7.00	97.9	7.4	75.33	3.36
8.00	97.6	7.2	76.00	2.93
8.48	97.3	7.0	76.67	2.75

APPENDIX D

PLENUM DESIGN

FIGURE D1: To Show the Dimensions of the Plenum



* All dimensions not to scale

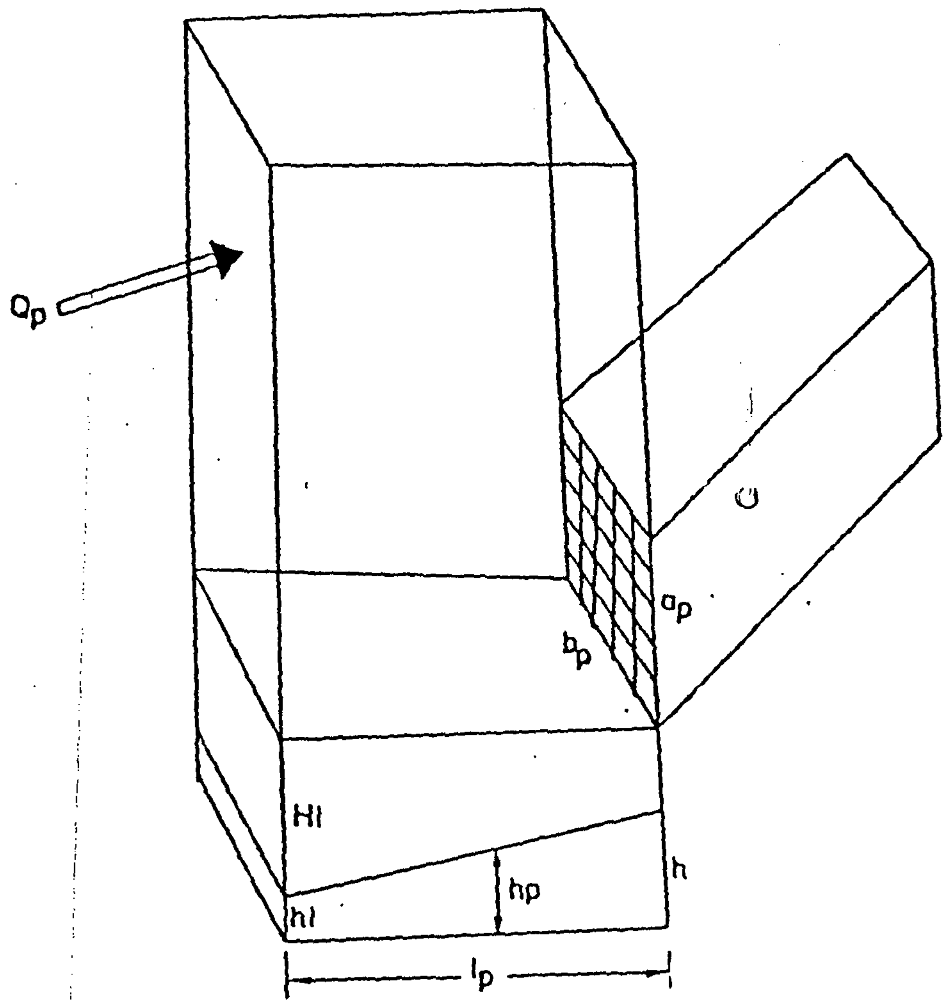


Fig. D-2 – Tube Bundle and the Plenum.

$$\text{Flow Velocity, } V = \frac{Q_p}{A_p} = \frac{Q_p}{a_p \cdot b_p}$$

$$\text{Amount of Sludge, } S_p = h_p\, l_p\, b_p$$

$$\therefore \quad h_p = \frac{S_p}{l_p\, b_p} = \frac{S_p\, a_p\, V}{l_p\, Q_p}$$

$$h_a = \frac{S_a\, a_a\, V}{l_a\, Q_a}$$

$$S_a = K\, S_p$$

$$Q_a = K\, Q_p$$

$$\therefore \quad h_a = \frac{K S_p\, a_a\, V}{l_a\, K\, Q_p}$$

$$\therefore \quad V = \frac{h_a\, l_a\, K\, Q_p}{K S_p\, a_a} = \frac{h_p\, l_p Q_p}{S_p\, a_p}$$

$$\text{ie.} \quad \frac{h_p\, l_p}{a_p} = \frac{h_a\, l_a}{a_a}$$

Subscript 'a' denotes actual condition ; 'p' refers to present condition.

$$\boxed{h_a = (l_p / l_a)\ (a_a / a_p)\ h_p}$$

TABLE D1-1

Plenum Design of the Inclined Tube Settler for Raw Water Turbidity of 36 NTU to 45 NTU

Flow : 8.0 l/min Average Effluent Turbidity: 5.8 NTU
Flow Velocity : 3.2 m/h Average Efficiency : 85.78 %
Overflow Rate : 10.70 m³/m² d Alum Concentration : 32 mg/l

Operating Time (h)	Raw Water Turbidity (NTU)	Flocculated water (NTU)	Effluent Turbidity (NTU)	Efficiency %	Temperature °C	Sludge Depth (cm)				
						X1	X2	X3	X4	X5
0	37	26	7.0	81.08	33	0.50	0.55	0.30	0.50	0.50
1	43	28	5.4	87.44	33	0.25	0.30	0.40	0.40	1.30
2	41	29	5.6	86.34	33	0.25	0.30	0.40	0.40	0.90
3	60	28	5.0	91.67	32	0.25	0.30	0.30	0.50	0.95
4	41	27	5.4	86.83	32	0.30	0.30	0.30	0.35	0.70
5	38	29	5.5	85.53	31	0.35	0.35	0.35	0.45	0.50
6	37	30	5.0	86.49	31	0.35	0.35	0.40	0.50	0.50
7	39	29	6.0	84.62	30	0.40	0.40	0.40	0.45	0.40
8	42	28	5.5	86.91	30	0.50	0.50	0.45	0.50	0.40
9	38	28	6.2	83.68	29	0.25	0.25	0.35	0.45	0.50
10	38	27	6.0	84.21	29	0.25	0.25	0.35	0.40	0.50
11	39	26	6.1	84.36	28	0.25	0.25	0.40	0.45	0.50
12	40	29	6.0	85.00	27	0.25	0.25	0.40	0.50	0.50
13	42	29	6.3	85.00	27	0.20	0.25	0.40	0.55	0.55
14	45	25	6.0	86.67	27	0.70	0.60	0.85	1.00	1.20

TABLE D1-1 Continue

15	40	29	6.2	84.50	28	0.45	0.35	0.40	1.10	1.75
16	36	24	6.1	83.06	28	0.35	0.35	0.30	0.60	0.40
17	40	29	6.0	85.00	29	0.35	0.35	0.25	0.35	0.50
18	40	23	6.0	85.00	29	0.25	0.30	0.30	1.35	2.00
19	41	24	5.2	87.32	30	0.45	0.45	0.40	1.45	0.85
20	43	28	6.0	86.05	30	0.15	0.20	0.35	0.40	0.40
21	42	20	6.0	85.71	30	0.10	0.20	0.65	0.30	0.35
22	43	39	9.2	78.61	31	0.00	0.00	0.90	0.70	0.80
23	42	28	9.7	76.90	31	0.00	0.00	0.20	0.35	0.35

TABLE D1-2

Plenum Design of the Inclined Tube Settler for Raw Water Turbidity of 36 NTU to 45 NTU

Flow : 15.0 l/min   Average Effluent Turbidity: 7.7 NTU
Flow Velocity : 6.0 m/h   Average Efficiency : 80.36 %
Overflow Rate : 20.07 m^3/m^2 d   Alum Concentration : 32 mg/l

Operating Time (h)	Raw Water Turbidity (NTU)	Flocculated Water (NTU)	Effluent Turbidity (NTU)	Efficiency %	Temperature °C	Sludge Depth (cm)				
						X1	X2	X3	X4	X5
0	38	28	19.0	50.00	27	0.50	0.50	0.40	0.50	0.85
1	37	29	9.0	75.68	27	0.80	1.00	1.20	1.95	2.35
2	40	29	7.5	81.25	28	0.50	0.70	0.70	0.90	1.65
3	36	21	7.3	79.72	28	0.60	0.65	0.60	0.85	0.75
4	45	28	7.0	84.44	29	0.65	0.55	0.60	0.95	1.00
5	40	27	7.1	82.25	29	0.40	0.50	0.60	0.75	0.80
6	39	26	7.2	81.54	29	0.40	0.35	0.50	0.95	0.80
7	35	29	7.0	80.00	30	0.40	0.30	0.50	0.90	0.70
8	40	29	8.0	80.00	30	0.55	0.60	0.55	0.65	1.15
9	39	27	9.0	76.92	31	0.40	0.40	0.70	0.95	1.10
10	40	28	8.0	80.00	31	0.35	0.45	0.50	0.60	0.85
11	40	29	14.0	65.00	31	0.50	0.55	0.80	1.40	1.40
12	41	30	16.0	60.98	32	0.60	0.60	1.40	1.80	1.50
13	40	29	17.0	57.50	32	0.40	0.45	0.70	0.50	0.65

TABLE D1-3

Plenum Design of the Inclined Tube Settler for Raw Water Turbidity of 36 NTU to 45 NTU

Flow	: 20.0 l/min	Average Effluent Turbidity	: 9.8 NTU
Flow Velocity	: 8.0 m/h	Average Efficiency	: 74.41 %
Overflow Rate	: 26.76 m^3/m^2 d	Alum Concentration	: 32 mg/1

Operating Time (h)	Raw Water Turbidity (NTU)	Flocculated Water (NTU)	Effluent Turbidity (NTU)	Efficiency %	Temperature °C	Sludge Depth (cm)				
						X1	X2	X3	X4	X5
0	41	25	12.5	69.51	32	0.00	0.00	0.00	0.00	0.00
1	37	29	10.0	72.97	32	0.80	0.90	0.95	1.20	1.30
2	38	28	9.5	75.00	32	0.70	0.75	0.95	1.10	2.00
3	39	27	9.5	75.64	33	0.85	0.95	0.85	1.50	2.20
4	39	26	9.0	76.92	33	0.50	0.50	0.75	1.30	1.30
5	39	28	10.0	74.36	33	0.40	0.40	0.45	0.90	0.80
6	39	28	10.0	74.36	33	0.10	0.30	0.30	0.70	0.80
7	38	27	10.0	73.68	32	0.80	0.75	0.90	1.20	1.25
8	38	26	10.5	72.37	32	0.50	0.55	0.75	1.00	1.00
9	39	27	15.0	61.45	31	0.50	0.60	1.00	1.00	1.00
10	40	29	16.0	60.00	31	0.35	0.35	1.00	0.80	0.80

APPENDIX E

LEAST SQUARE METHOD OF ANALYSIS

TABLE E1-1

Using LEAST SQUARES METHOD to Find the Relationship Between Flow Velocity Against the Depth of Settled Sludge After 8 Hours of Operation

Flow Velocity (m/h)	X lnV	Yx1 ln hx1	Yx5 ln hx5	X^2 $(\ln V)^2$	$Yx1^2$ $(\ln hx1)^2$	$Yx5^2$ $(\ln hx5)^2$	XYx1 lnV.lnhx1	XYx5 lnV.lnhx5
3.2	1.16315	0.97456	1.73165	1.35292	0.94977	2.99861	1.13356	2.01417
6.0	1.79176	1.45862	2.21920	3.21040	2.12757	4.92485	2.61350	3.97627
8.0	2.07944	1.53687	2.34660	4.32407	2.36220	5.50653	3.19583	4.87961
Sum	5.03435	3.97004	6.29746	8.88739	5.43940	13.4299	6.94289	10.87005

$hx1 = 0.6389V + 0.25075$
$hx5 = 0.6679V + 0.94490$
$rx1 = 0.983$ $rx1^2 = 96.64\ \%$
$rx5 = 0.993$ $rx5^2 = 98.70\ \%$

Let assuming the fitting function as

$$h = aV^b$$
$$\ln h = (\ln a) + b(\ln V)$$

For x1,

$\ln a = 0.25075$, implies $a = 1.28499$
$b = 0.63917$

Therefore,

$$h = 1.28499V^{0.63917}$$

For x5,

$\ln a = 0.94448$, implies $a = 2.57147$
$b = 0.68608$

Therefore,

$$h = 2.57147V^{0.68608}$$

Ref: DANIEL, C. et al (1971), MOSTELLER, F. et al (1977) and WALPOLE, R.E. et al (1978).

TABLE E1-2

Using LEAST SQUARES METHOD to Find the Relationship Between Flow Velocity Against the Depth of Settled Sludge After 16 Hours of Operation.

	Flow Velocity (m/h)	X lnV	[1]Yx1 ln hx1	[1]Yx5 ln hx5	X^2 $(\ln V)^2$	$Yx1^2$ $(\ln hx1)^2$	$Yx5^2$ $(\ln hx5)^2$	XYx1 lnV.lnhx1	XYx5 lnV.lnhx5
	3.2	1.16315	1.66770	2.42480	1.35292	2.78120	5.87970	1.93980	2.82050
	6.0	1.79176	2.15180	2.91240	3.21040	4.63030	8.48210	3.85570	5.21830
	8.0	2.07944	2.23000	3.03970	4.32407	4.97290	9.23980	4.63710	6.32090
Sum		5.03435	6.04950	8.37690	8.88739	12.3844	23.6016	10.4321	14.3597

$hx1 = 0.6383V + 0.94540$
$hx5 = 0.6882V + 1.63740$
$rx1 = 0.982$ $rx1^2 = 96.42\%$
$rx5 = 0.998$ $rx5^2 = 99.65\%$

Let assuming the fitting function as

$h = aV^b$

$\ln h = (\ln a) + b(\ln V)$

For x1,

$\ln a = 0.94540$, implies $a = 2.57400$
$b = 0.63830$

Therefore,

$h = 1.28499V^{0.63917}$

For x5,

$\ln a = 1.6374$, implies $a = 5.14306$
$b = 0.68823$

Therefore,

$h = 2.57147V^{0.68808}$

Ref: DANIEL, C. et al (1971), MOSTELLER, F. et al (1977) and WALPOLE, R.E. et al (1978).

[1]Sludge depth is double that of the 8 hours operation period, neglecting the effect compaction.

TABLE E1-3

Using LEAST SQUARES METHOD to Find the Relationship Between Flow Velocity Against the Critical Plenum Depth

	Flow Velocity (m/h)	X lnV	Yx1 ln hx1	Yx5 ln hx5	X² (ln V)²	Yx1² (ln hx1)²	Yx5² (ln hx5)²	XYx1 lnV.lnhx1	XYx5 lnV.lnhx5
	3.2	1.16315	2.86220	2.12226	1.35292	8.19219	4.50399	3.32917	2.46851
	6.0	1.79176	2.94180	2.52573	3.21040	8.65421	6.37931	5.27100	4.52550
	8.0	2.07944	2.98820	2.64262	4.32407	8.92936	6.98344	8.92936	5.49517
Sum		5.03435	8.79220	7.29061	8.88739	25.77576	17.8667	14.81395	12.48918

$hx1 = 0.13574V + 2.70294$
$hx5 = 0.57992V + 1.45702$
$rx1 = 0.965 \qquad rx1^2 = 99.08\ \%$
$rx5 = 0.995 \qquad rx5^2 = 99.04\ \%$

Let assuming the fitting function as

$h = aV^b$

$\ln h = (\ln a) + b(\ln V)$

For x1,

$\ln a = 2.70294$, implies $a = 14.92354$, $b = 0.13574$

Therefore,

$h = 14.92354V^{0.13574}$

For x5,

$\ln a = 1.45702$, implies $a = 4.293164$, $b = 0.579923$

Therefore,

$h = 4.293164V^{0.57992}$

Ref: DANIEL, C. et al (1971), MOSTELLER, F. et al (1977) and WALPOLE, R.E. et al (1978).

TABLE E1-4

Using LEAST SQUARES METHOD to Find the Correlation Factor For Various Column Settling Depths

	Settling Depth (y=cm)	S.F. (X)	y^2	X^2	xy
	2.8	10.0	7.84	100.0	28.0
	1.5	30.0	2.25	900.0	45.0
	1.2	52.5	1.44	2756.25	63.0
	0.5	72.0	0.25	5184.00	36.0
	0.175	100.0	0.31	10000.0	17.5
Sum	6.175	264.5	11.811	18940.25	189.5

Therefore,

$$S.F. = 2.7014-0.02772hc$$

TABLE E1-4

Using LEAST SQUARES METHOD to Find the Correlation Factor For Various Column Settling Depths

	Settling Depth (y=cm)	S.F. (X)	y^2	X^2	xy
	2.8	10.0	7.84	100.0	28.0
	1.5	30.0	2.25	900.0	45.0
	1.2	52.5	1.44	2756.25	63.0
	0.5	72.0	0.25	5184.00	36.0
	0.175	100.0	0.31	10000.0	17.5
Sum	6.175	264.5	11.811	18940.25	189.5

Therefore,

$$S.F. = 2.7014-0.02772hc$$