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Optimising Final Clarifier Design and Performance of an Activated Sludge Plant using Mathematical Modelling

Peter Ojo and Augustine O. Ifelebuegu

Abstract— **The aim of this paper was to establish a sizing safety decision boundary for a successful clarifier design and performance in an activated sludge wastewater treatment plant. The key objectives are to propose an alteration to the internal hydrodynamic characteristic of the final clarifier by determining the surface area and side wall depth of the clarifier using the WRC and ATV1991 design approach, and predict the clarification and thickening condition within the final clarifier using both the solid flux (pitman and white 1984 & Wahlberg and keinath 1998) and state point analysis. The methodology involved collecting site specific data from a wastewater treatment plant situated in the West Midlands, under different operating condition A to D and using a one dimensional mathematical model developed based on solid flux theory to analyse the results. The optimised sizing safety decision for final clarifier design and performance for site specific condition B (3.0kg/m³ MLSS, 110mg/l SSVI, 31.46 Ø and eight final clarifiers) was 3.5kg/m³ MLSS, 80mg/l SSVI, 31.46 Ø and six final clarifiers. This achieved a sustainable clarification and thickening efficiency. Clarifiers were under loaded and safe for operation with no indication of a solid washout. Significant savings in cost and footprint reduction was also achieved.**

Keywords— Final Clarifier, Mixed Liquor Suspended Solids Stirred Sludge Volume Index, Permissible Flux (P), Actual Flux State Point and Solid Flux Theory

I. Introduction

Designed over one hundred years ago, activated sludge plant which is a form of wastewater treatment works, has been responsible for about 50 % of all wastewater treated by biological oxidation in the United Kingdom (RAE 1998). Although, this includes four distinct treatment stages namely, preliminary treatment like grit removal, primary treatment, secondary (biological) treatment and tertiary treatment (Simutis et al 2004). However, this paper focuses on the biological treatment stage specifically the final clarifier (FC). Although, the final clarifier has been known as the most vital unit operation in an activated sludge process but will fail in its clarification and thickening function outside its co-dependency on the aeration process. More so, the type of settling occurring within the final clarifier is the zone settling, where the flocculated particles settles together as layers or zone that are hydraulically sustained . Following this further, it is important to mention that clarification occurs within the final clarifier when the solids are separated from the liquid phase to produce a clarified effluent low in effluent suspended solids (ESS).

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On the other hand, thickening occurs when there is a conveyance of the sludge particles to the bottom of the clarifier with slightly evident return activated sludge (under flow). Though, clarification accounts for less than (<) 2 % of the solids applied to the clarifier but a rise in ESS will contribute to clarification failure. In contrast, thickening will account for about 98% solid fraction but a rise in sludge blanket depth contributes to the thickening failure. However, to have a robust final effluent discharged to receiving rivers that will be void of ESS permit violation and reduced sludge retention time (SRT) associated with unplanned wasting of suspended solids (SS) with the final effluent, then a sustainable improvement in both the final clarifier design and performance become necessary. Consequently, it has been reported in the West Midland Infrastructure 2010 that the wastewater infrastructure is in an average condition needing some consideration and devotion to investment, particularly in relation to footprint reduction and sustainability of the wastewater treatment (ICE 2010). The European legislation has equally introduced tighter consent and the necessity to treat bigger volumes of flow from growing towns and cities has caused pressure on the existing systems (EA 2011). Further still, to meet this tighter consent, improving performance of the final stages of the activated sludge process becomes necessary as the final clarifier determines the capacity of the activated sludge plant and the fate of the final effluent quality (Burt et al 2005).The Aim of this study is to:

Establish a sizing safety decision boundary for a successful clarifier design and performance in a wastewater treatment plant situated in the west midlands.

This study is intended to:

Propose an alteration to the internal hydrodynamic characteristic of the final clarifier by determining the surface area and side wall depth of the clarifier using the WRC and ATV1991 design approach.

Predict the clarification and thickening condition within the final clarifier using both the solid flux (pitman and white 1984 & Wahlberg and keinath 1998) and state point an***alysis.***

II. Background

The key criteria used for the assessment of final clarifier design and performance of the activated sludge plant are hydraulic overflow rate (m/h), solid loading rate (kg TSS/m²/h), sludge volume loading rate(m³/m²/h) and weir overflow rate (m³/m/h). The modelling approach used for improving the final clarifier design and performance was based on the Water Research Council (WRC) design, German Abwasser Technische Vereinigung (ATV) design and Solid Flux Theory (SFT) methods. The WRC design method is based on the solid flux theory and has been known to adapt conditions and sludge characteristics predominant in the United Kingdom (UK). More so, the $SSVI_{3.5}$ index was correlated to the values of the settling constants which resulted to an empirical equation (Eqn. 2) used to determine the maximum allowable solid loading rate (white 1975). On the other hand, ATV 1991 defines the surface area of the final clarifier by the maximum sludge volume loading rate and it establishes that a higher loading rate allowed was in the boundary of (sludge volume < 450l/ m²/h). Conversely, the solid flux theory is used as a tool for sizing clarifiers and is based on one dimensional (1D) settling and provides the best possible performance of a final clarifier.

In addition, the area required for hindered settling is a function of the solid flux analysis. This is because the area required for thickening of the applied mixed liquor depends on the limiting solid flux that can be transported to the bottom of the clarifier. However, data derived from settling test conducted to determine the mixed liquor concentration and settling rate was made available when applying the solid flux theory. This clarifier operated at a steady state with a constant flux of solids moving downward and hence the mass flux of solids due to hindered or gravity settling obeyed the equation of mass flux solid at any point in a clarifier as in Equation 1. Following this further, the solid theory criteria in Equation 2-5 was used in assessing the final clarifier performance and the solid flux operating curves was improved by making changes to some hydrodynamic characteristics of the clarifier like side wall depth, numbers of tanks, tank diameter (∅), floor angle, floor slope, McKinney baffle MLSS concentration and flow rates etc.

$$SF_u = C_i U_b \,(1\text{kg}/10^3\,\text{g}) = C_i \,{}^{Q_u}/_{A} (1\text{kg}/10^3\,\text{g}) \quad (1)$$

Where,

SF_u = Solid flux due to gravity (kg/m².h)

C_i = concentration of solids at the point in question (g/m³)

V_i = settling velocity of solids at concentration C_i, m/h

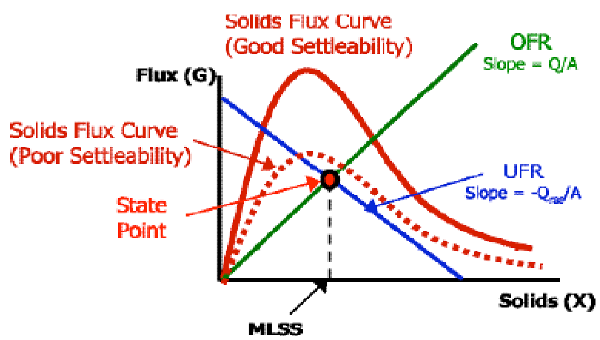

Fig 1.0 Element of State Point Analysis (Source Jeneyanayagam 2006)

III. Design Approach

A. *Solid Flux Theory*

The solids flux theory approach used to determine the area required for hindered settling and thickening are based on criterions. This will be considered below.

B. *Solid flux theory criterion*

1) Criterion 1a: solid loading rate

It states that final clarifier must not be overloaded in thickening and the actual solid flux applied to the tank (j_{QF}, kg/m²h) must always be less than the limiting rate of the solid flux reaching the bottom of the FST (j_L, kg/m²h) called limiting flux (Ekama et al 1997). This is the expressed below:

$$j_{QF} < j_L \quad (2)$$

Where,

j_{QF} = Actual solid flux applied to clarifier

j_L = limiting flux

But,

$j_{QF} = X (Q_i + Q_r) \backslash A$

Where,

X = Solids concentration (kg/m³)

Q_i = Influent rate (m³/h)

Q_r = Return activated sludge (RAS) recycling rate

A= Surface area of final clarifier (m²)

However,

$j_L = 8.85(100 / SSVI_{3.5})^{0.77} (Q_r/A)^{0.68}$

Where

$SSVI_{3.5}$ = Stirred sludge volume index

2) Criterion I (b): Critical Underflow Velocity

It was reported by Ekama et al 1997 that Criterion I (a) was only valid up to the critical underflow velocity (U_b).

3) Criterion II: Hydraulic Overflow Rate

It was stated that final clarifier must not be overloaded in clarification i.e. the hydraulic loading rate must not exceed the sludge settling velocity (Ekama et al 1997). However, assuming sludge settling velocity as a unique function of the solids concentration the expression below was valid:

$$Q_i/A \leq v_o \exp(-n.X) \quad (3)$$

Where,

Q_i = Influent rate (m³/h)

v_o = Vesilind settling velocity

n = Free settling parameter or coefficient

4) Criterion III: Volumetric Loading Rate

This was defined as the product of the actual solid loading rate and the SSVI. However, the volumetric loading rate ($q_{sv}= Q_{sv}/ A$) should be less than (<) 500l/m²h (**Ekama et al 1997**). This was expressed as follows:

Volumetric loading rate (VLR) = Q_{sv}/ A (4)

But

$$Q_{sv}/ A = X.\frac{Q_i}{A}(\frac{4}{3}\ SSVI_{3.5})$$

Where,
q_{sv} = Volumetric loading rate
Q_i = Influent rate m³ / h

5) Criterion IV: Weir Loading Rate

It was deduced that the effluent flow rate per length of overflow weir offers a guide to the flow velocities in the vicinity of the weir. However, typical value of weir loading rate should be maintained below [10 m³/h.m], but for light sludge's a reduced value of [5 m³/h.m] was projected (Ekama et al 1997). Furthermore, for larger clarifiers the limits were increased by 50% and the weir loading rate was reported by Ekama et al 1997 to be of great relevance to criteria I and II respectively. This was expressed as follows:

WLR = weir loading rate = $Q_e = \frac{Q_i}{L}$ (5)

Where,

Q_i= Influent rate (m³ / h)

L = Total weir length (m)

Q_e = Weir loading rate (m³/h. m)

Subsequently, another method of clarifier analysis considered in improving the clarifier design and performance is the state point analysis (SPA). This is an extension of the solids flux analysis used to describe the movement of solids through a clarifier. Also, it is based on site specific data which makes optimising clarifier size and lowering design safety factors satisfactory. More so, because the solid removal mechanism in final clarifiers are predominant type III settling (zone settling), it entails the settling of flocculated particles as a blanket (zone) with particles maintaining position relative to each other. The zone settling velocity (ZSV) is a function of MLSS concentration (X) and this is represented by the vesilind equation (Equation 6-10).

ZSV = $V_o\ e^{-KX}$ (6)

G = (ZSV) X (7)

Combining (2) and (3)

G= (X *V_o) * e^{-kX} (8)

Where,
V_o and K = settling constants obtained from series of settling tests
G = Solid flux (kg /m²/d)

The X and G values were generated by performing series of settling test at different MLSS concentrations. The realised solid flux curves was developed by plotting G on the y-axis and X on the x-axis respectively. More so, the two (2) operating parameters of a final clarifier, overflow rate (OFR) and underflow rate (UFR) shown as straight lines were obtained as slope values from superimposing the operating parameters on the solid flux curve. The OFR and UFR are expressed as follows:

OFR = $\frac{Q}{A}$ (9)

UFR = $\frac{-Q_{RAS}}{A}$ (10)

Where,
A = Clarifier surface area, m²
Q = Influent flow (m³/d)
Q_{RAS} = RAS flow (m³/d)

The final clarifier performance in clarification was predicted by the location of the state point (sp) in relation to the solid flux curve, which allows site specific OFR to be established. Furthermore, there are different clarification conditions that can occur in the clarifier namely:

- ***Under loaded*** – state point (sp) situated within the flux curve and the effluent suspended solid (ESS) level is low (settling velocity > OFR).
- ***Critically loaded*** – state point (sp) situated on the solid flux and the ESS level is high (settling velocity = OFR)
- ***Overloaded*** – state point (sp) located outside the solid flux curve and ESS level is high (settling < OFR)

The final clarifier performance in thickening was predicted by the location of the UFR operating straight line in relation to the descending arm of the solid flux curve. Furthermore, there are different thickening conditions that can occur in the final clarifier namely:

- ***Under loaded*** – UFR line contained within the flux curve and no significant solid accumulation nor appreciable sludge blanket (SLR < limiting flux).
- ***Critically loaded*** – UFR line is tangential to the descending arm of the solid flux and there is a formation of a sludge blanket (SLR = limiting flux)
- ***Overloaded*** – UFR line intersects the descending arm of the solid flux curve and there exist a resultant solid accumulation and deep sludge blanket

formation. Consequently, if not curtailed there is a possibility of a net transfer of solids from aeration tank to the clarifier. Also, a continuity of sludge blanket occurrence results in loss of solids in the final effluent (clarification failure).

IV. Result

Table IV shows the site data and constant flow data from the wastewater treatment plant been investigated. It was observed from Table IV that optimization of the existing plant could be conducted at different state point within the Final clarifier so as to achieve a better sedimentation resulting to an improved effluent quality in response to the tighter consent from urban waste water treatment directive(UWWTD) 2006. More so, according to Metcalf and Eddy 2004 and Gray 2004, a conventional activated sludge plant MLSS should range from 1.5g/l to 3.5 g/l but for a high rate plant can be up to 8.0g/l. Also, the SSVI values should be at least 100mg/l for a plant without associated filamentous growth but a less than 100ml/g is a more desired value. However, a value greater than 150 ml/g depicts a treatment works associated with filamentous growth. In achieving this consent the by existing process conditions like the MLSS, SSVI, tank numbers and the tank existing dimensions like the tank diameter will be optimised.

Consequently, Table IV shows that the FFT (m^3/day) and DWF (m^3/day) were vital as the former represents the maximum flow that can be treated by the plant which was 100000 m^3/day while the latter implies average daily flow to the treatment plant during the 7days of no rain and following 7days during which the rainfall did not exceed 0.25mm in any of the days (Gray 2004), was 42857 m^3/day. This indicates that when surface water finds its way to the treatment plant via the sewers after rainfall the wastewater becomes diluted and constitutes a constraint of how much waste water the plant will treat. However the provision for DWF in the design avoided this constraint.

Table IV.1 Wastewater Treatment Plant Site and Flow Data

S/N	Parameter	Condition			
		A	B	C	D
	Plant Site Data				
1	MLSS (g/l)	2.8	3.0	3.3	3.3
2	SSVI(ml/g)	110.0	110.0	120.0	120.0
3	Tank Diameter (m)	29.49	31.46	27.03	31.09
4	Tank Diameter (m)	8.0	8.0	8.0	8.0
	Plant Flow Data				
1	FFT (m^3/day)	100000.0	100000.0	100000.0	100000.0
2	DWF (m^3/day)	42857.0	42857.0	42857.0	42857.0
3	Normal = 1.2 * DWF (m^3/day)	51428.4	51428.4	51428.4	51428.4
4	RAS = 0.5 * DWF (m^3/day)	21428.4	21428.4	21428.4	21428.4
5	Max RAS = 1.5 * DWF (m^3/day)	64285.5	64285.5	64285.5	64285.5

Evaluation of Existing Condition A

It was observed from Table IV.2 and Fig.2 that for the *condition A***,** the intersection of the underflow rate line (UFR), Influent concentration and overflow rate line (OFR) were within the solid flux curve (SFC) for both pitman and white (1984) and wahlberg and keinath (1998). More so, the UFR line was below the descending limb of the flux curve which depicts an underloaded condition for clarification and thickening for the Final clarifier. This is an indication of a safe operation in its thickening function as solid loading rate (SLR) < limiting flux rate hence no significant solid accumulation and no appreciable sludge blanket while for its clarification function it was deduced that there is safe operation as the settling velocity > OFR and hence low effluent suspended solids (ESS) was formed .

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Table IV.2: Existing Data for Condition A

S/N	Parameter	Condition A
1	Number of FC (N)	8.0
2	Full Flow to Treatment (FFT), m^3/hr	4,166.67
3	RAS Flow Rate(Max RAS),m^3/hr	2678.56
4	Tank Diameter (Ø), m	29.49
5	SSVI , ml/g	110.0
6	Influent MLSS,kg/m^3	2.8

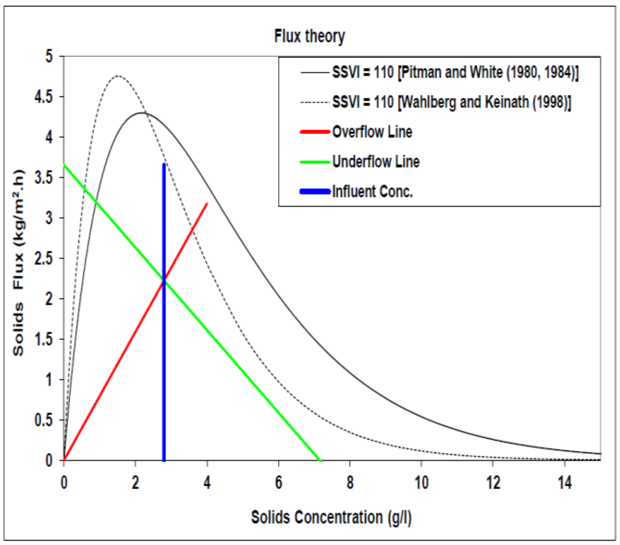

Fig. 2 Existing Final Clarifier (Solid Flux Curve for Condition –A)

However, a better operational curve can be obtained by improving the operational parameters like MLSS and SSVI. A new process condition of *2.5 kg/m³ MLSS and 80ml/g SSVI (Table IV.3)* was used and a new operational curve was realised from Fig. 3 which shows a better sedimentation.

Table IV.3 Improved Data for Condition A

S/N	Parameter	Condition A
1	Number of FC (N)	8.0
2	Full Flow to Treatment (FFT), m^3/hr	4,166.67
3	RAS Flow Rate(Max RAS),m^3/hr	2678.56
4	Tank Diameter (Ø), m	29.49
5	SSVI , ml/g	80.0
6	Influent MLSS,kg/m^3	2.5

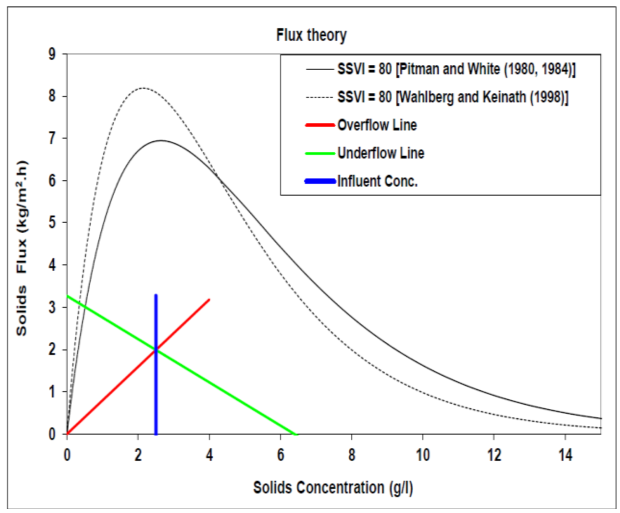

Fig .3 Improved Final clarifier (Solid Flux Curve for Condition- A)

A. *Evaluation of Existing Condition B*

It was observed from *Table IV.4 and Fig.4* that for *condition B***,** the intersection of the underflow rate line (UFR), Influent concentration and overflow rate line (OFR) were within the solid flux curve (SFC) for both pitman and white (1984) and wahlberg and keinath (1998). More so, the UFR line was below the descending limb of the flux curve which depicts an underloaded condition for clarification and thickening for the Final clarifier. This is an indication of a safe operation as solid loading rate (SLR) < limiting flux rate. Therefore, no significant solid accumulation and no appreciable sludge blanket. Moreso, because the settling velocity > OFR then a low ESS was realised.

Table IV.4: Existing Data for Condition B

S/N	Parameter	Condition
		B
1	Number of FC (N)	8.0
2	Full Flow to Treatment (FFT), m^3/hr	4,166.67
3	RAS Flow Rate(Max RAS),m^3/hr	2678.56
4	Tank Diameter (Ø), m	31.46
5	SSVI , ml/g	110.0
6	Influent MLSS,kg/m^3	3.0

Table IV.5 Improved data for condition B

S/N	Parameter	Condition
		B
1	Number of FC (N)	6.0
2	Full Flow to Treatment (FFT), m^3/hr	4,166.67
3	RAS Flow Rate(Max RAS),m^3/hr	2678.56
4	Tank Diameter (Ø), m	31.46
5	SSVI , ml/g	80.0
6	Influent MLSS,kg/m^3	3.5

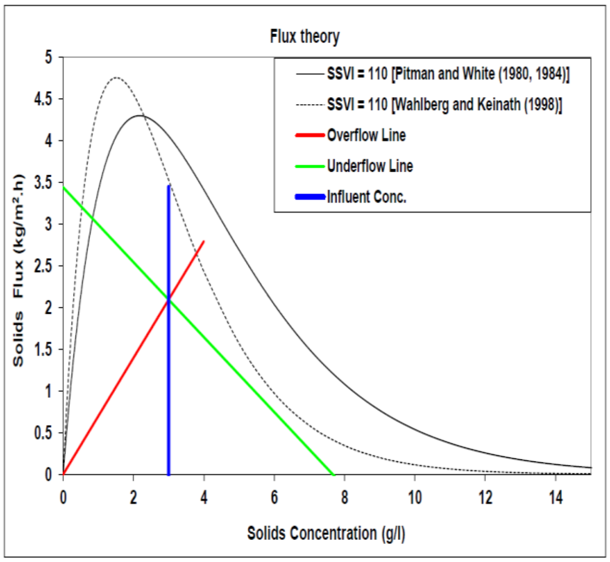

Fig 4.0 Existing Final Clarifier (Solid Flux Curve for Condition B)

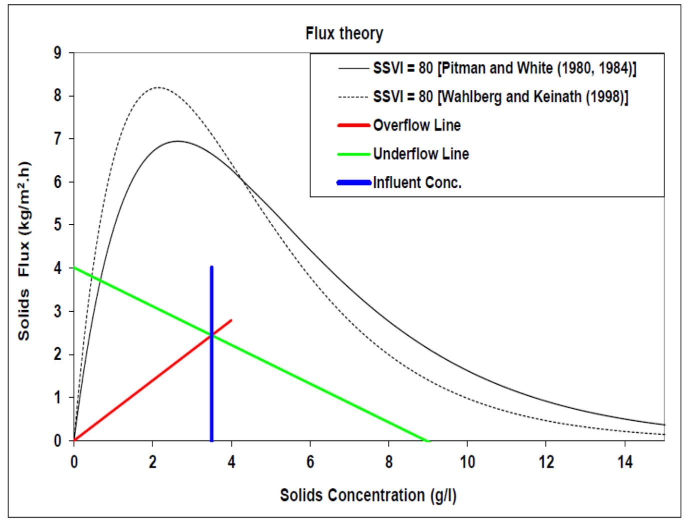

Fig .5 Optimised Final Clarifier (Solid Flux Curve for Condition B)

However, a better operational curve can be obtained by improving the operational parameters like MLSS and SSVI. A new process condition of *3.5 kg/m³ MLSS, 80ml/g SSVI and 6FC* ***(Table IV.5)*** was used and a new operational curve can be viewed from Fig.5 which shows a better sedimentation. In addition, there was a reduction in the clarifier foot print from eight (8) clarifiers (table IV.4) to six (6) clarifiers (table IV.5), saving significant cost and footprint.

B. *Evaluation of Existing Condition C*

It was observed from **Table IV.6** and **Fig.6** that for **condition C,** the intersection of the underflow rate line (UFR), Influent concentration and overflow rate line (OFR) were within the the solid flux curve (SFC) for Pitman and White (1984). More so, the UFR line intersects the descending limb of the flux curve which depicts an over loaded condition for both clarification and thickening function of the FST. Since the UFR line intersects the descending arm of the flux curve then significant sludge accumulation and deep sludge blanket occurs interms of thickening. Consequently, interms of clarification within the Final clarifiers, the settling velocity < OFR and solid carry over occurs leading to a high effluent suspended solids(ESS).

However, considering the pitman and white curve (1984) , from table IV.6 and fig.6, it can be observed that the statepoint sp C was below the flux curve and the UFR line was tangential to the descending limb of the flux curve which depicts an underloaded condition for clarification and critically loaded condition for thickening. It is an indication that for clarification the settling velocity > OFR and hence a low ESS, while for thickening the SLR = limiting flux and hence a sludge blanket was formed.

Table IV.6 Existing Data for condition C

S/N	Parameter	Condition
		C
1	Number of FC (N)	8.0
2	Full Flow to Treatment (FFT), m^3/hr	4,166.67
3	RAS Flow Rate(Max RAS),m^3/hr	2678.56
4	Tank Diameter (Ø), m	27.03
5	SSVI , ml/g	120
6	Influent MLSS,kg/m^3	3.3

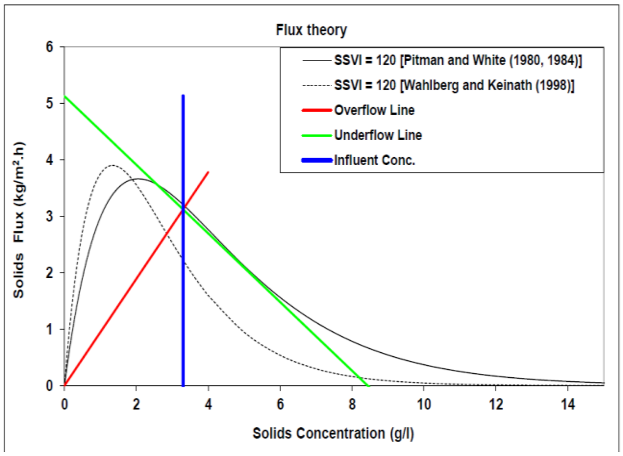

Fig. 6 Existing Final Clarifier (Solid Flux Curve for Condition C)

However, from the fig.6 it was deduced that the tank failed in both its thickening and clarification fuction with respect to (wrt) the Pitman and White Curve (1984) since it was criticaly loaded . Hence to improve this condition, the ***3.3 kg/m³ MLSS was lowered to 2.5 kg/m³ MLSS, reduce the feed solids by converting to a step feed system (Fig.7) and the return active sludge (RAS) rate was increased.*** More so, the tank failed in both its thickening and clarification fuction with respect to (wrt) the Wahlberg and Keinath Curve (1998) since it was overloaded. Therefore the number of tanks were increased to reduce the rise rate. In using a new process condition of ***2.5 kg/m³ MLSS, 80ml/g SSVI and 10 FSTs (TableIV.7)*** a new operational curve was realised as shown in Fig.8 which depicted a better sedimentation and thickening function.

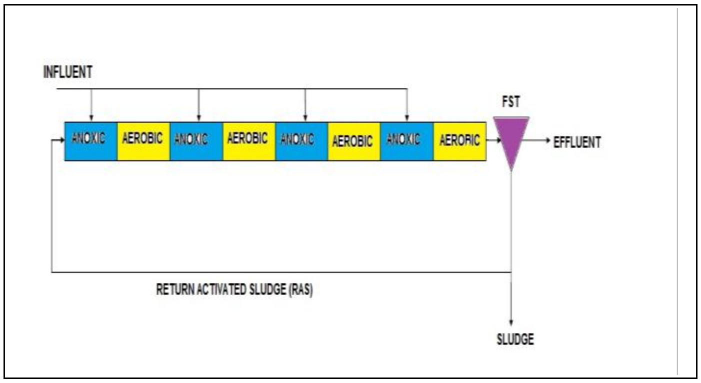

Fig.7 Step Feed Configuration (Source: Metcalf and Eddy, Inc. 2004)

Table IV.7 Improved Data for condition C

S/N	Parameter	Condition
		C
1	Number of FC (N)	10
2	Full Flow to Treatment (FFT), m^3/hr	4,166.67
3	RAS Flow Rate(Max RAS),m^3/hr	2678.56
4	Tank Diameter (Ø), m	31.46
5	SSVI , ml/g	80
6	Influent MLSS,kg/m^3	2.5

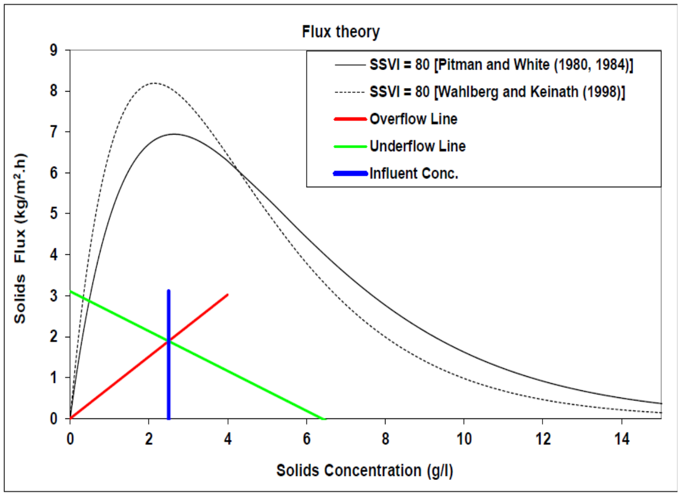

Fig.8 Improved Final Clarifier (Solid Flux Curve for Condition C)

C. *Evaluation of Existing Condition D*

It was observed from **Table IV.8** and **Fig.9** that for **condition D,** the intersection of the underflow rate line (UFR), Influent concentration and overflow rate line (OFR) were within the the solid flux curve (SFC) for Pitman and White(1984) but with reference to the wahlberg and keinath curve (1998) it was observed that the intersection of the underflow rate line (UFR), Influent concentration and overflow rate line (OFR) were outside the solid flux curve (SFC) and the UFR line intersects the descending limb of the flux curve. This indicates that for the pitman and white flux curve condition, the tank will be underloaded and sludge washout will be avoided in terms of thickening while the settling velocity > OFR with low ESS. Consequently, it indicates that for wahlberg and keinath curve condition it will be overloaded in both clarification and thickening. Therefore, in terms of clarification settling velocity < OFR and solid carry over will result in high ESS while in interms of thickening, there will be significant solid accumulation and deep sludge blankets.

Table IV.8 Existing Data for condition D

S/N	Parameter	Condition
		D
1	Number of FC (N)	8
2	Full Flow to Treatment (FFT), m^3/hr	4,166.67
3	RAS Flow Rate(Max RAS),m^3/hr	2678.56
4	Tank Diameter (Ø), m	31.09
5	SSVI , ml/g	120
6	Influent MLSS,kg/m^3	3.3

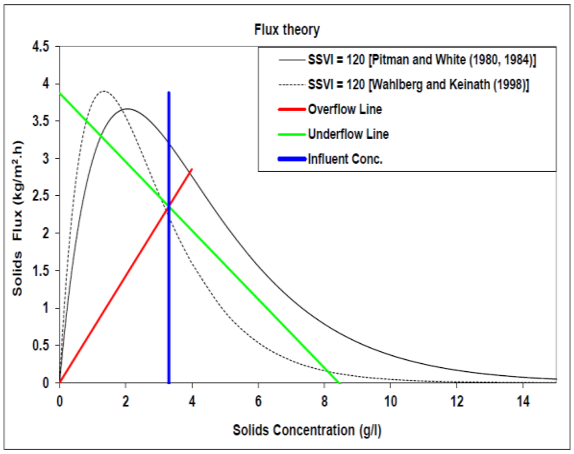

Fig.9 Existing Final Clarifier (Solid Flux Curve for Condition D)

However, from the Fig 20.0 it was deduced that the tank failed in both its thickening and clarification fuction with respect to (wrt) the wahlberg Curve (1998) since it was overloaded loaded. Therefore the number of tanks were increased to reduce the rise rate. In using a new process condition of ***2.5 kg/m³ MLSS, 80ml/g SSVI and 10 FSTs (TableIV.9)*** a new operational curve was realised as shown in Fig.10 which depicted a better sedimentation and thickening function.

Table IV.9 Improved Data for condition D

S/N	Parameter	Condition
		D
1	Number of FC (N)	10
2	Full Flow to Treatment (FFT), m^3/hr	4,166.67
3	RAS Flow Rate(Max RAS),m^3/hr	2678.56
4	Tank Diameter (Ø), m	31.09
5	SSVI , ml/g	80
6	Influent MLSS,kg/m^3	2.5

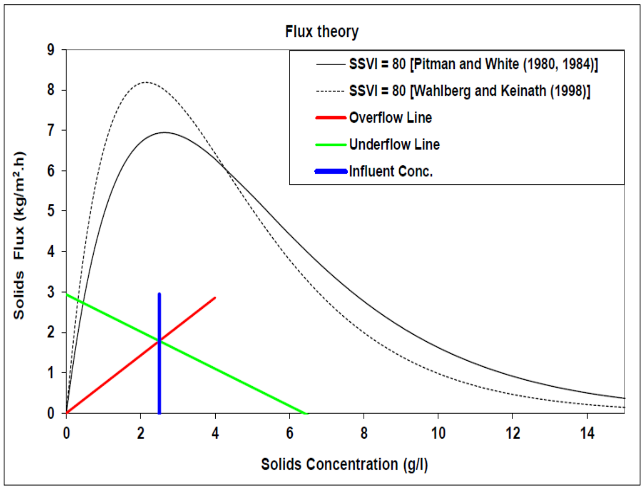

Fig.10 Improved Final clarifier (Solid Flux Curve for Condition D)

V. Conclusion

The improved sizing safety decision for final clarifier design and performance for site specific condition A to D were as follows: *(2.5kg/m^3 MLSS, 80mg/l SSVI, 29.49m Ø and 8 FST), (3.5kg/m^3 MLSS, 80mg/l SSVI, 31.46 Ø and 8 FST), (2.5 kg/m^3 MLSS, 80 mg/l SSVI, 27.03m Ø and 10 FST) and (2.5 kg/m^3 MLSS, 80 mg/l SSVI, 31.09m Ø and 10 FST).* This will achieve a sustainable clarification and thickening efficiency. Tank will be under loaded and safe for operation with no indication of a solid washout.

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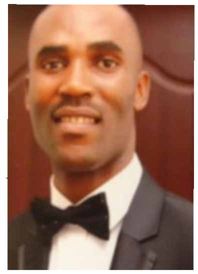

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