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USC Chemical Engineering Student

Analysis and Design of Particle Handling and Treatment Operations

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DESIGN OF A CONTINUOUS THICKENER FOR A WASTEWATER TREATMENT FACILITY

A design project submitted in partial fulfillment of the requirements in the course

CHE 3213/W
Analysis and Design of Particle Handling and Treatment Operations

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CHAPTER 1: INTRODUCTION

Theoretical Background

Separation of solid and liquid phases is the most common phase separation requirement in process industries and involves various techniques as shown in Figure 1.

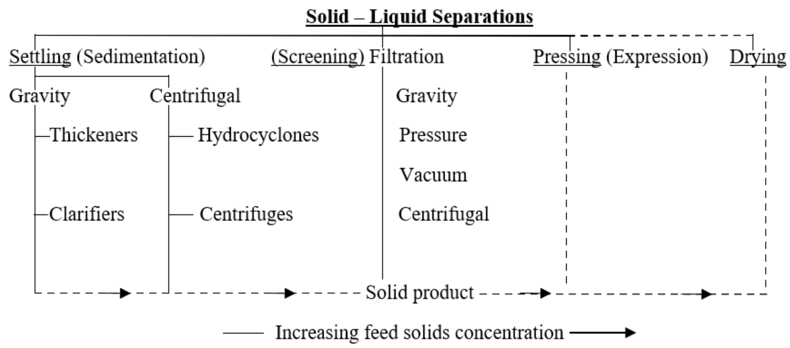

Figure 1. Solid-Liquid Separation Techniques

In sedimentation processes, thickening is the separation of the liquid components of a suspension in order to achieve a denser product and a pure liquid flow. The purpose of the process may be to thicken the pulp or to extract the liquid from a suspension (Towler et al., 2022).

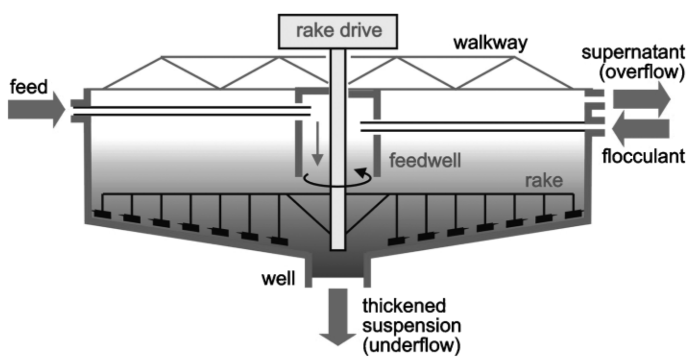

Figure 2. Sectional View of a Circular High Rate Thickener

Thickeners are circular tanks either with a flat bottom or a gentle fall towards the center with a conical sludge hopper where sludge is drawn by a rotating rake. The depth of the tank depends on the nature of sludge and its thickening ability. Sludge is introduced in a central feed well at a depth of around 1 meter below the surface level of water. As sludge enters the thickener, flocs are formed and will start to settle, causing the free water to rise that is then collected over an outlet weir. By the time the flocs reach the bottom of the tank, there is no free water left since they were already compressed and dewatered (Binnie et al., 2018).

Problem Statement

A coagulation-flocculation process is utilized in a wastewater treatment facility to reduce the Total Suspended Solids (TSS) content found in the wastewater stream generated in a food industry. After this process, wastewater containing the floc smust be clarified while the flocs are allowed to settle that is to be collected separately in a continuous thickener. The thickening process is expected to increase the solid content while reducing free water volume, minimizing unit load on downstream processes.

Shown in table below are some of the characteristics of the wastewater containing the flocs that is subjected into the thickener.

Table 1. Wastewater Characteristics

Parameters	Unit	Value
Temperature of Influent Wastewater	^oC	27
pH of Influent Wastewater with Flocs		6.0
Dry Density of the Flocs (expected thickened sludge from the thicker)	g/cm^3	1.5
Density of the Wastewater, ρ	kg/m^3	996.54
Influent Solid Concentration, X_0	kg/m^3	100
Underflow Solid Concentration, X_u	kg/m^3	400
Feed Rate, Q_0	m^3/hr	350

A batch settling study of the sludge was carried out in a $50.5\ mm$ diameter glass cylinder with a height of $1\ m$ and a capacity of $2L$ at $100\frac{g}{L}$ initial concentration. The interface heights in mm at a particular time in minutes are shown in Table 2.

Table 2. Interface Height as a Function of Time of Settling Sludge at 100 g/L initial concentration

Time (mins)	Interface Height (mm)	Time (mins)	Interface Height (mm)
0	860	64	391.5
2	838	74	357
4	817.5	85	326
8	780	102	285.5
13	735	120	250
18.5	688	141	215.5
26	625.5	162	193.5
32	574	180	177.5
43	498.5	300	150
52	446.5	1440 (∞)	98

Schematic Diagram

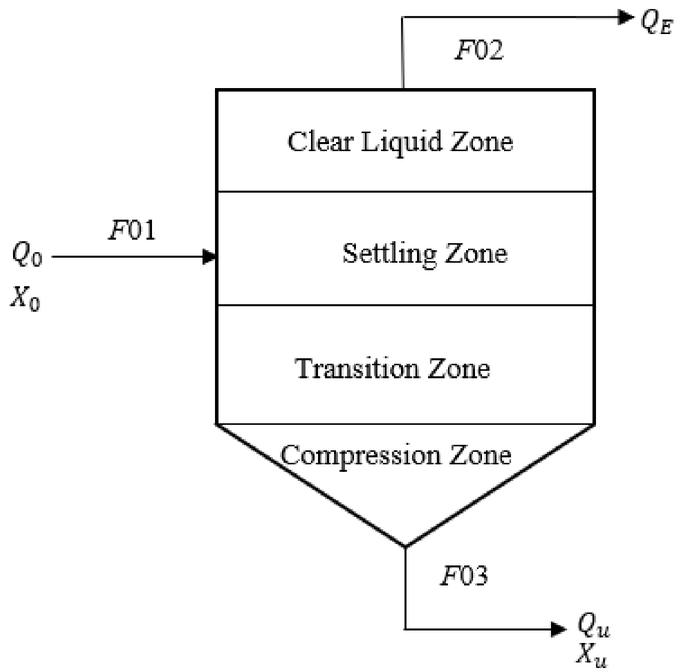

Figure 3. Schematic Diagram of a Thickener

Problem Assumptions

Several assumptions were made in designing the continuous thickener. Among these assumptions are the following:

- No solid exit from the overflow.
- The density of the wastewater is equal to the density of the water.
- The solid particles are equal in such a way that they are of the same size, shape, and density.

CHAPTER II: ENGINEERING DESIGN CALCULATIONS

Chemical Engineering Design

Diameter and area

The mass balance for solids in a thickener

$$Q_0X_0 = Q_uX_u + Q_eX_e \quad [1]$$

where Q_0X_0 is the flow of solids into the thickener, Q_uX_u is the flow of solids into the underflow and Q_eX_e is the flow of solids in the clarified effluent.

Since a very small amount of solids typically escapes with the clarified effluent; hence, X_e is approximately zero. The material balance can be rewritten into

$$Q_0X_0 = Q_uX_u \quad [2]$$

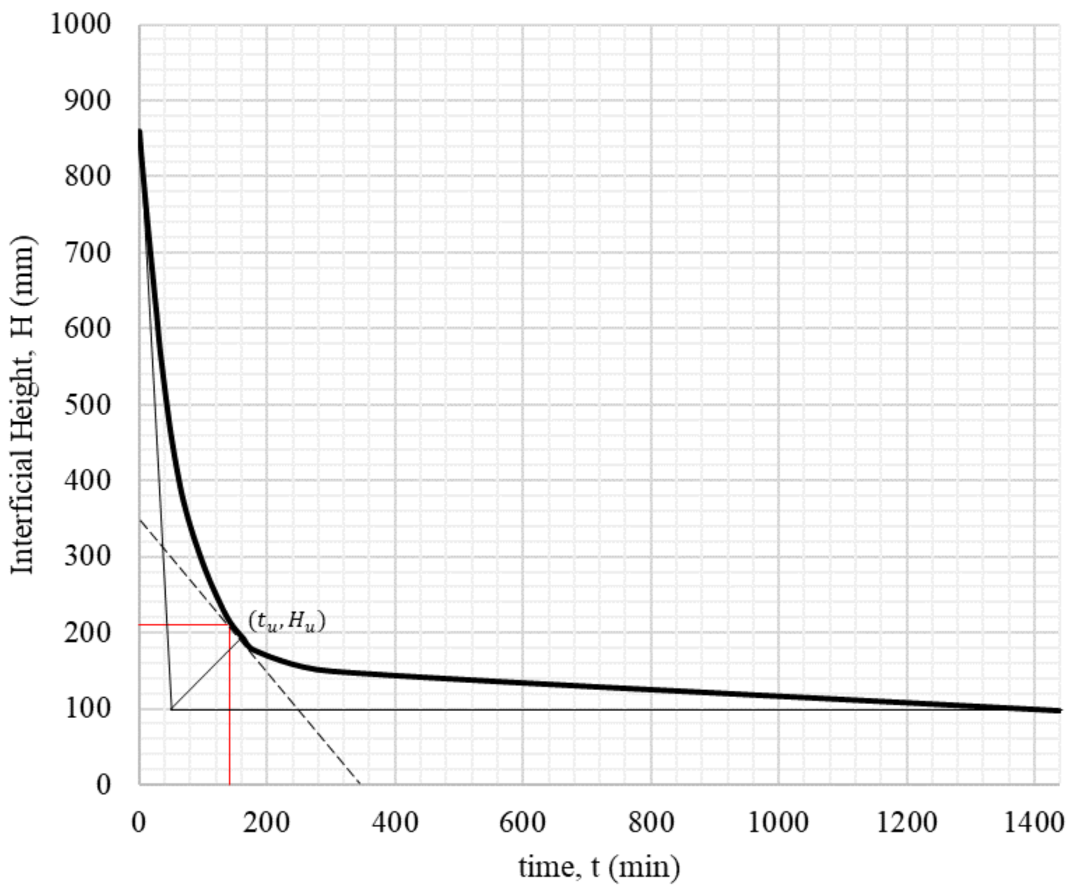

Figure 4. Interface height vs time *t*

The underflow line, as defined by Talmadge and Fitch (1955), is the horizontal line determined from the required underflow concentration in a continuous thickener. From the material balance, the underflow line is determined using the equation,

$$H_u = \frac{H_0 X_0}{X_u} = \frac{(0.86\, m)(100\, \frac{kg}{m^3})}{400\, \frac{kg}{m^3}} = 0.215\, m \qquad [3]$$

where H_u is the interface height of the underflow in meter, H_0 is the influent interface height in meter, X_0 is the influent solid concentration and X_u is the underflow solid concentration in kilograms per cubic meter.

The time to achieve the desired concentration in the underflow (t_u) is found to be at approximately 142 minutes based on figure 4. This can also be verified using the table below wherein at 141 minutes, the concentration of solids in the underflow is already at approximately 399.0719 kg/m^3 and its corresponding underflow height is 215.15 mm. Hence, it could be that the concentration at 142 minutes will be at the desired underflow concentration which is 400 kg/m^3 with an interface height of the underflow of 215 mm.

Table 3. Concentration of solids in the underflow at point time t

Time (mins)	Interface Height (mm)	Concentration of Solids in the underflow (kg/m^3)
0	860	100
2	838	102.6253
4	817.5	105.1988
8	780	110.2564
13	735	117.0068
18.5	688	125
26	625.5	137.49
32	574	149.8258
43	498.5	172.5176
52	446.5	192.6092
64	391.5	219.6679
74	357	240.8964
85	326	263.8037
102	285.5	301.2259

120	250	344
141	215.5	399.0719
162	193.5	444.4444

The thickener cross-sectional area can be calculated as shown,

$$A = \frac{Q_0 t_u}{H_0} = \frac{(350\ \frac{m^3}{hr})(142\ min)(\frac{1\ hr}{60\ mins})}{0.86\ m} = 963.18\ m^2 \quad [4]$$

where A is the cross-sectional area of the thickener in square meters, and t_u is the time to achieve the desired concentration in hours.

Table 4. Multiplying factors and allowances for different thickener parameters

Parameters	Allowances
	20% for diameter > 30 m
*Cross-section area of tank	50% for diameter < 4.6 m
	10-25% for safety
*Compression zone depth	75%
*Transition depth	2 m
**Clear liquid zone	0.5 m
**Feed zone	0.6 m
**Pitch of the bottom	0.3 m
**Irregularities in discharge	0.3 m

**Green, D. and Southard, M. (2018). Perry's chemical engineers' handbook. 9th ed.*
***Unit Operations of Particulate Matter. (2017b, July 3). Sedimentation and batch sedimentation test-2*

In order to ensure the integrity of the equipment wherein variations in feed characteristics such as temperature, pH, particle size and solid concentration as well as the turbulence of the feed is incorporated, a safety factor used in thickening. The safety factor recommended for the design of thickeners can be shown in Table 4. The factor allowances used were 20% for diameter that are greater than 30 meters, and another 20% for safety.

$$A' = F_1 F_2 A = (1.2)(1.2)(963.18\ m^2) = 1386.98\ m^2 \quad [5]$$

where F is the safety factor, A' is the actual cross-sectional area, and A is the computed cross-sectional area of the thickener.

From the actual cross-sectional area, the diameter of the thickener can be obtained.

$$D = \sqrt{\frac{4A'}{\pi}} = \sqrt{\frac{(4)(1386.98\ m^2)}{\pi}} = 42.02\ m \quad [6]$$

where D is the diameter of the thickener in meters.

Table 5. Thickener diameter and area using Talmadge and Fitch method

Parameters	Value
Underflow interface height, H_u (m)	0.215
Time to achieve the desired concentration, t_u (hr)	2.37
Cross-sectional area, A (m^2)	963.18
Actual cross-sectional area (with safety factor), A' (m^2)	1386.98
Diameter, D (m)	42.02

The required cross-sectional area to obtain an underflow concentration of 400 kg/m^3 is approximately 963.18 m^2; however, a total of 44% additional allowance in the area is attributed to the feed characteristics variations, safety, and the feed turbulence. Hence, the actual cross-sectional area is 1386.98 m^2 and a diameter of 42.02 m.

Depth

The height of the thickener can be determined by initially obtaining the depth of the compression zone within the retention time ($t_u \approx t_c$). The critical time is defined as the sedimentation time wherein only two layers are visible–the clear liquid zone and the compression zone. Hence, the solid volume in the compression zone at $t=t_c$ is equal to the total volume of solids that is fed. Thus, the volume of the compression within the retention time is the summation of the volume of solids and the liquid available in the compression zone which can be mathematically expressed as,

$$V_C = \frac{Q_0X_0}{\rho}(t_u - t_c) + Q_0X_0\int_{t_c}^{t_u}[\frac{1}{X_L} - \frac{1}{\rho}]dt \quad [7]$$

where V_C is the compression volume, $t_u - t_c$ is the retention time, and $\frac{1}{X_L} - \frac{1}{\rho}$ is the fraction of liquid in the compression zone.

Simplifying the equation,

$$V_C = Q_0 X_0 \int_{t_c}^{t_u} [\frac{1}{X_L}] dt \qquad [8]$$

A more accurate value of the critical time is determined through the semi-log plot of $(H - H_\infty)/(H_0 - H_\infty)$ vs time, *t* as shown in figure 5.

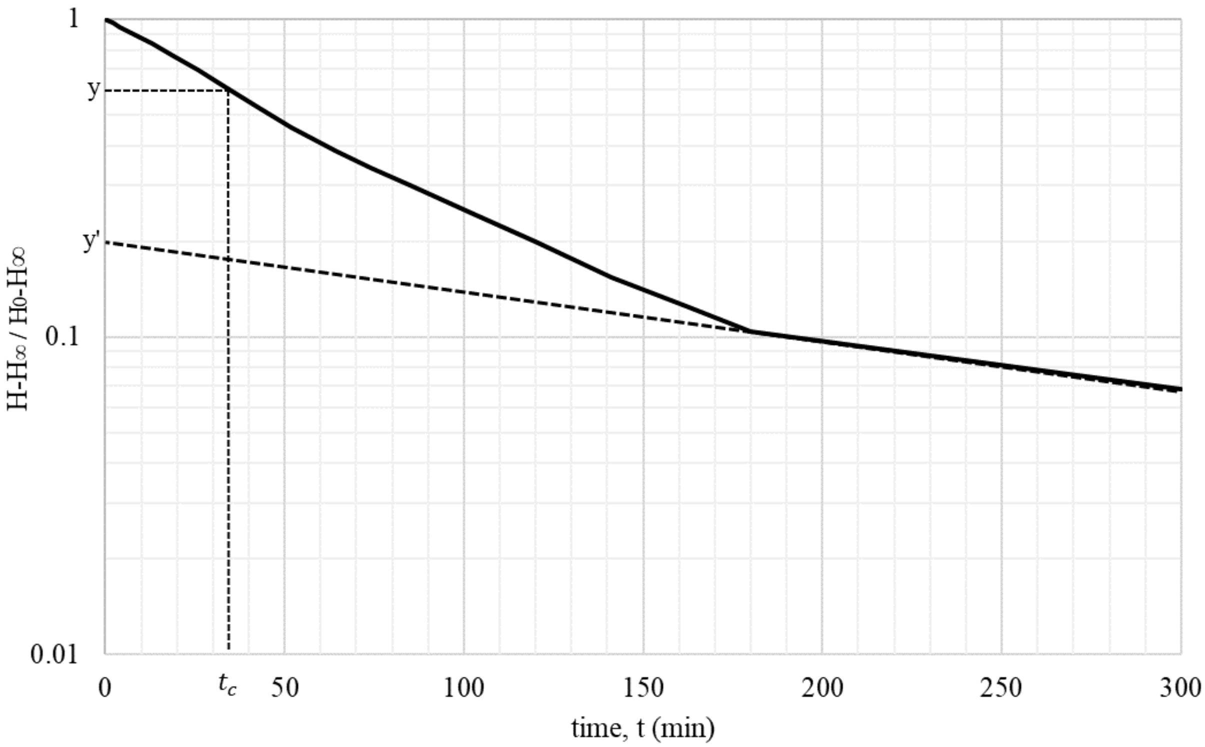

Figure. 5. Plot of H-H$_\infty$/H$_0$-H$_\infty$ vs time

Initially, by extending the linear compression zone, the value that intersects the y-axis is the *y'-value*. This is used to determine another value which is the *y-value*. The *y-value* is obtained by employing the equation shown below. The time that corresponds to the *y-value* is the critical time.

$$y = \frac{1+y'}{2} = \frac{1+0.2}{2} = 0.6 \qquad [9]$$

It is found in the figure above that the *y'-value* is equal to 0.2, and the *y-value* is 0.6. The corresponding *x-value* of the determined *y-value* is approximately 34 minutes. Thus, the critical time t_c is 34 minutes.

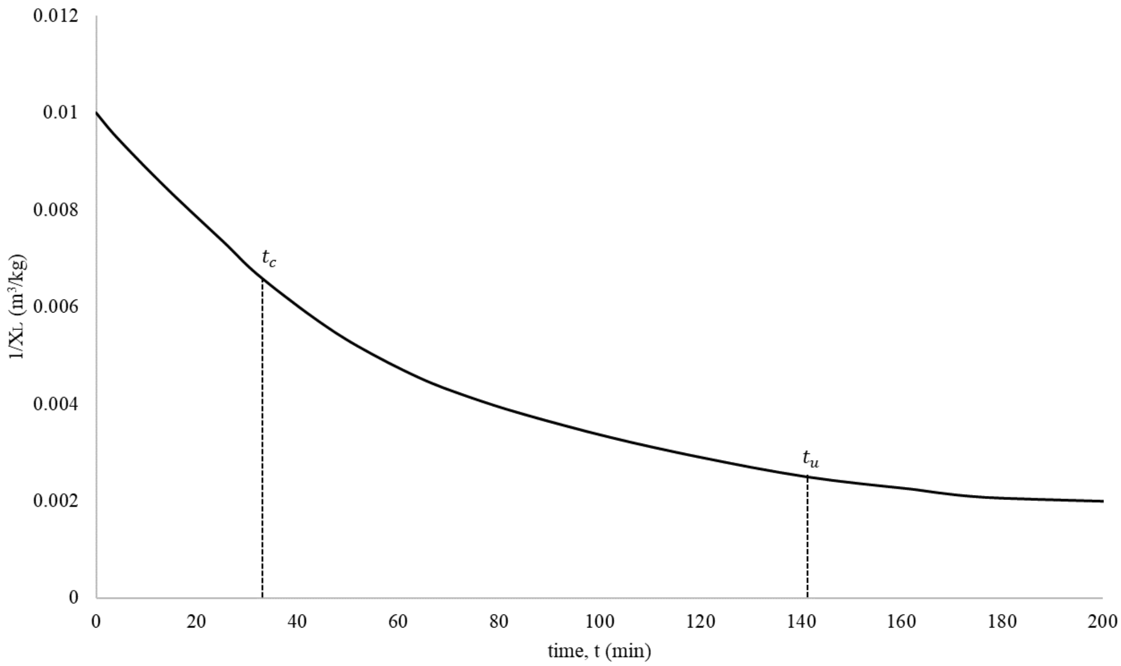

Figure 6. 1/X_L vs time *t*

The volume of the compression zone can be evaluated by finding the area under the curve with a lower limit t_c of 34 minutes, and upper limit t_u of 142 minutes. By numerical integration using the trapezoidal rule, the area under the curve is 0.44 m^3 per kilogram of solids. Hence, by substituting the determined values to equation 8, compression zone to contain a supply of solids per cross-sectional area.

$$h = 1.75\frac{V_C}{A'} = (1.75)(\frac{257.0478\ m^3}{1386.98\ m^2}) = 0.3489\ m \qquad [10]$$

where V_C is the volume of the compression zone and A' is the actual thickener area. A multiplication factor of 175% is attributed to the height allowance of the compression zone.

The total depth of the tank would be the required depth with the additional allowances shown in Table 4 to account for the lost space due to the pitch of the drag in the thickener, and depth of feed. Moreover, each zone must also have height allowances (Unit Operations of Particulate Matter, 2017).

$$h' = h + allowances = 0.3489\ m + 3.7\ m = 4.05\ \text{m} \qquad [11]$$

where *h* is the required thickener depth

Table 6. Volume of compression zone, critical time, and thickener depth.

Parameters	Value
Volume of the compression zone, V_C (m^3)	257.0478
Critical time, t_c (hr)	0.57
Required thickener depth, h (m)	0.35
Total thickener depth (with height allowances), h' (m)	4.05

The required thickener height is approximately 0.35 m. To account for lost space due to the drag pitch, and to add allowances for every zone, the total thickener depth is 4.05 m.

Mechanical Engineering Design

Floor Slope

The design of this thickener for the specified usage and process conditions will follow the standard floor slope given by Ovivo Water, an arm of Valmet Forward that designs and manufactures equipment for different industries. The standard floor slope for thickeners was set at 2.75:12. The standard conical discharge for thickeners is set at 45º.

Rake Arm

Rake arms in thickeners extend across the radius of the thickener, scraping the sludge towards the exit at the bottom of the thickener. Using the standard floor slope of thickeners, which is 2.75:12, the angle of inclination of the rake can be calculated using equation 12.

$$\theta = tan^{-1}(\frac{y}{x}) = tan^{-1}(\frac{2.75}{12}) = 12.91° \quad [12]$$

The length of the rake inclined on the floor across the thickener can be calculated using equation 13. Noting that this length will be for one rake and typically large, heavy duty thickeners have two rakes connected across the diameter of the thickener with optional small rake arms higher than the long main thickeners at the bottom.

$$L_{rake} = \frac{r}{cos\,\theta} = \frac{21.01\,m}{cos\,12.91°} = 21.5549\,m \quad [13]$$

Where L_{rake} is the length of one rake arm, r is the radius of the thickener, and θ is the angle of inclination of the rake arm.

Wall thickness

In calculating the thickness of the tank, factors such as hoop tension or tangential stress and the modular ratio of the chosen cement grade must be considered. Since the thickener is made of concrete at low pressure, the wall thickness can be calculated using the equation,

$$\sigma_{concrete} \geq \frac{H}{[1000T + (m-1)A_{steel}} \qquad [14]$$

Where $\sigma_{concrete}$ is the permissible stress for direct tension of M40 grade concrete, H is the tangential stress, m is the modular ratio, and A_{steel} is the area of the steel, and T is the thickness of the thickener.

The tangential stress is related to the hydrostatic pressure, and the diameter of the thickener. This relationship is shown in equation 15 wherein,

$$H = \frac{PD}{2} = \frac{(\rho_w g h^2)D}{2} = \frac{(996.54\,\frac{kg}{m^3})(9.8\,\frac{m}{s^2})(4.05\,m)^2(42.02\,m)}{2} = 3365556\,N \qquad [15]$$

where P is the hydrostatic pressure, and D is the thickener diameter. The hydrostatic pressure can be expressed in terms of the product of the density of the wastewater to the gravitational acceleration and thickener's height squared.

Since steel is tougher and stiffer compared to concrete, a modular ratio is used to correlate some of the characteristics of steel in the chosen concrete grade. In this case, M40 concrete is used. The permissible compressive stress in concrete in bending of M40 grade concrete is 13 N/mm^2.

$$m = \frac{280}{3\sigma_{cbc}} = \frac{280}{3(13\,\frac{N}{mm^2})} = 7.17949\,\frac{mm^2}{N} \qquad [16]$$

where σ_{cbc} is permissible compressive stress in concrete in bending of M40 grade concrete.

The area of steel in tension can be obtained by equation 17. The permissible tensile stress of steel is 205 N/mm^2.

$$A_{steel} = \frac{H}{\sigma_{steel}} = \frac{3365556\,N}{205\,\frac{N}{mm^2}} = 16417.3497\,mm^2 \qquad [17]$$

where σ_{steel} is the permissible tensile stress of steel.

The thickness of the thickener is found to be 1651.44 mm or 1.651 m using equation 14 by substituting the determined values from equations 15-17. The permissible stress for direct tension of M40 grade concrete is 1.92 N/mm^2.

$$1.92 \geq \frac{3365556\,N}{[1000T + (7.17949-1)(16417.3497\,mm^2)}; T = 1.651\,m$$

Feed well

The feed well design ensures that the feed enters the thickener with minimal turbulence and uniform distribution while dissipating most of the kinetic energy. To avoid excess velocity, the open launder, through which the feed enters, should have a slope of no more than 2%. The feed well must also have a diameter of 15% to 25% of the thickener and a height of 30%-75% of the thickener height (Voutchkov, 2017).

$$D_{feed\,well} = 0.15D = (0.15)(42.02\,m) = 6.30\ m \quad [18]$$

$$h_{feed\,well} = 0.50h' = (0.50)(4.05\,m) = 2.03\ m \quad [19]$$

Sludge well

The resulting sludge is retrieved in the sludge well which is positioned at the bottom of the thickener. The diameter of the sludge well is typically 10% to 13% that of the diameter of the thickener.

$$D_{sludge\,well} = 0.13D = (0.15)(42.02\,m) = 5.46\ m \quad [20]$$

Table 7. Thickener specifications

Thickener specifications	Value
Rake arm Length, (m)	21.5549
Angle of inclination, (◦)	12.91
Wall thickness, T (m)	1.651
Feed well diameter, $D_{feed\ well}$ (m)	6.30
Feed well height, $h_{feed\ well}$ (m)	2.03
Sludge well diameter, $D_{sludge\ well}$ (m)	5.46

Material Selection

Wastewater or sludge treatment processes are implemented to reduce odors, pathogens, biodegradable toxins, and solids in wastewater which is accomplished before reusing or the final disposal of wastewater (Woodard et al., 2006). For the construction of the sludge thickener, several functional requirements were considered like the pH and toxicity of the wastewater, applied load of the waste water, and corrosive conditions of the wastewater. With the following in mind, the most suitable material was selected in terms of its mechanical properties, chemical compatibility to the substances in the wastewater, and cost.

The thickener tank design should be based on adequate strength and sufficient resistance to cracking to avoid leakage. With this, concrete is employed as the main material for the construction of the tank, sludge well and feed well. According to IS 3370: 2009 which is the code of practice for design of concrete structure for liquid storage, a leak free tank can be achieved by selecting a cement grade of M20 and above (Adhikari, 2018). Therefore, M40 grade will be used due to its high strength for direct tension and tension due to bending. However, since the thickener is subjected to tangential stress proportional to the amount of wastewater it will contain, the concrete will be reinforced with steel so that it can support the weight of the water effectively (Chmielewskiet al., 2020).

Reinforced concrete is a common material used in wastewater facilities because it is economical and low-cost in terms of construction and maintenance, however, exposure to harsh wastewater conditions which include pH of wastewater, the amount of acidophilus sulfur-oxidizing microorganisms and sulphuric acid present in wastewater accelerates the deterioration of the concrete surface – eventually attacking the steel reinforcement (Parande et al., 2006). In order to avoid the corrosion of the reinforced concrete, it is necessary to apply a migrating corrosion inhibitor on the concrete. MCI-2005 which is a liquid concrete admixture that protects steel reinforcement. Employing this admixture inhibits corrosion from the start without compromising the concrete’s physical properties. Furthermore, it is suitable for wastewater because of its low solubility according to the ANSI/NSF 61 standard for use in potable water structures.

It is also important to consider the corrosion resistance of a material of the rake and scraper given that they would always come in contact with a sludge. Incorporating SS 304 as the material for the rake and scraper is economically sound since it does not experience thinning and a corrosion allowance is not required when used in wastewater conditions. Unlike in carbon steel, aeration processes do not lead to higher rates of corrosion in SS 304 and a chemical additive is not required in order to maintain its chemical resistive properties. Additionally, it has good formability and high tensile strength which is useful for the rake and scraper (Fattah-alhosseini & Vafaeian, 2015). Because of these properties, stainless steel would be utilized in the assembly of the rake and scraper. Additionally, stainless steel will be used for the thickener's platform, walkway, handrail, feedwell, and anchor bolts.

Reinforced concrete with M40 grade cement will be used to design the tank of the thickener. MCI-2005 will be added to the concrete to protect the steel reinforcement from corrosion. The rotating rake and scraper will be constructed using SS304 The platform, walkway, handrail, feedwell, overflow weir, and anchor bolts will also be using SS304.

Design Specification

Thickener Specification Data Sheet

Equipment Tag:	T-001	Equipment Name:	Thickener
Service:	Wastewater Treatment	Plant:	Wastewater Treatment Facility
		Site:	Food industry

OPERATING CONDITIONS

Influent Wastewater temperature [°C]:	27°C		
Volumetric feed flow rate [m^3/hr]:	350	Overflow Solid Concentration [kg/m^3]:	0
Influent Solid Concentration [kg/m^3]:	100	Underflow Solid Concentration [kg/m^3]:	400

SPECIAL CONDITIONS

	YES	NO
Stress Relieve	☐	☒
Vessel in Lethal Service:	☐	☒
Vessel in Wet Sour Service:	☐	☒
Cyclic Service:	☐	☒

No. of Cycles/Year/Design Life: N/A

CONSTRUCTION

Part	Material	Corrosion Allowance
Thickener	M40 Cement grade reinforced concrete	N/A
Sludge well	M40 Cement grade reinforced concrete	N/A
Feed well	M40 Cement grade reinforced concrete	N/A
Rake	Stainless steel 304	N/A

INTERNALS

Description	Unit Weight (kg)	Liquid Holdup Vol %	Pressure (atm)
Rake	N/A	N/A	N/A

INSULATION

Type: None

FIREPROOFING

☐ YES ☒ NO
☐ Inside Skirt ☐ Outside Skirt
☐ Insulated or Fireproofed skirts to have sleeved openings
☐ Saddles

SPECIFICATIONS			
Tank			
Thickness [m]:	1.651	Depth [m]:	4.05
Diameter [m]:	42.02		
Rake			
Dimensions [mm, º]:	21.55; 12.91		
Feed Well			
Diameter [m]:	6.30	Height [m]:	2.03
Sludge Well			
Diameter [m]:	5.46		

CHAPTER III: DESIGN ILLUSTRATIONS

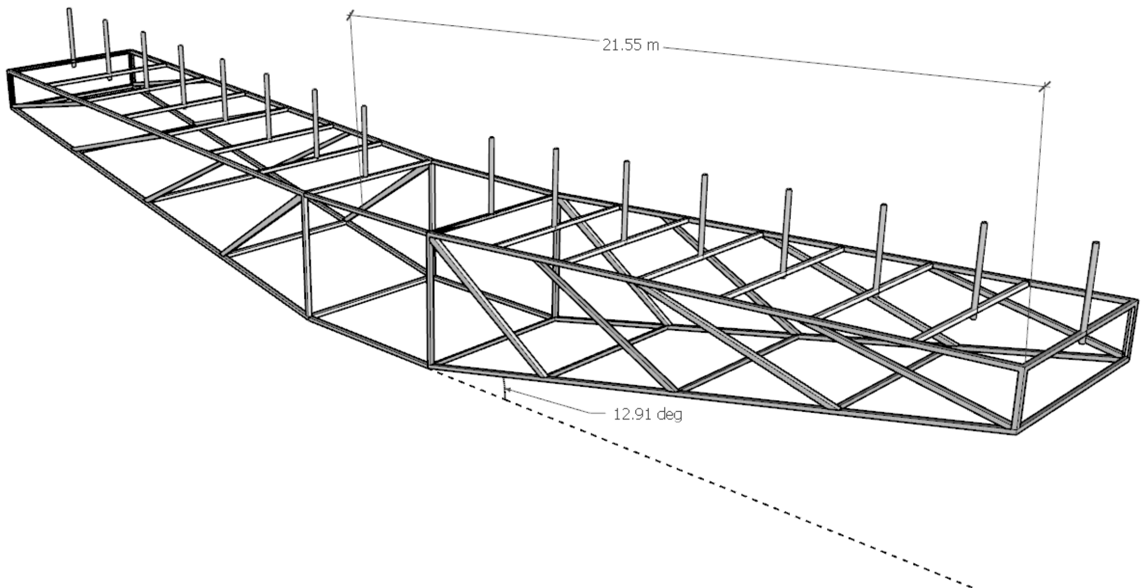

Figure 7. Rake design

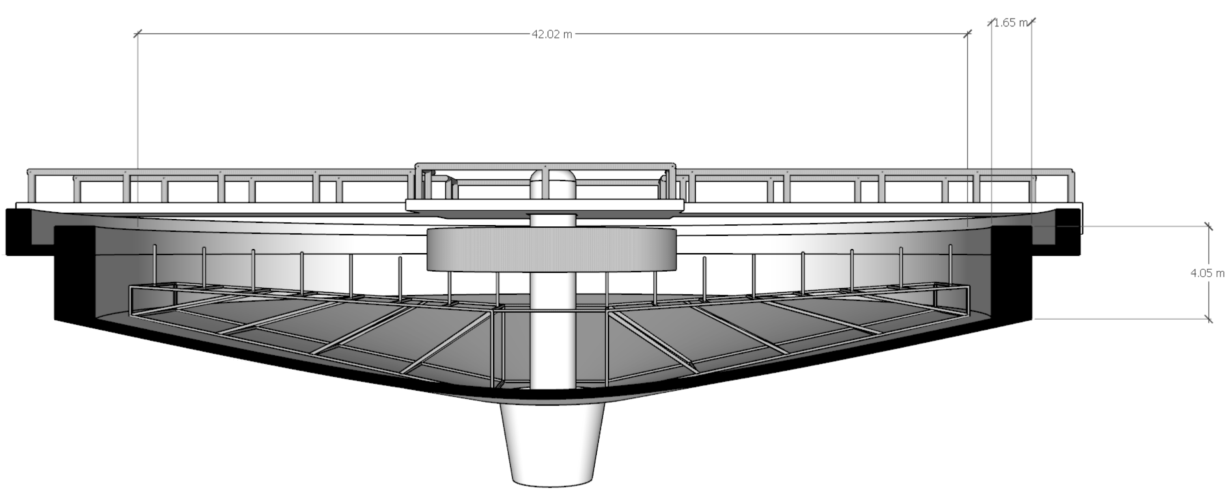

Figure 8. Front View of the Cross-section of the thickener design

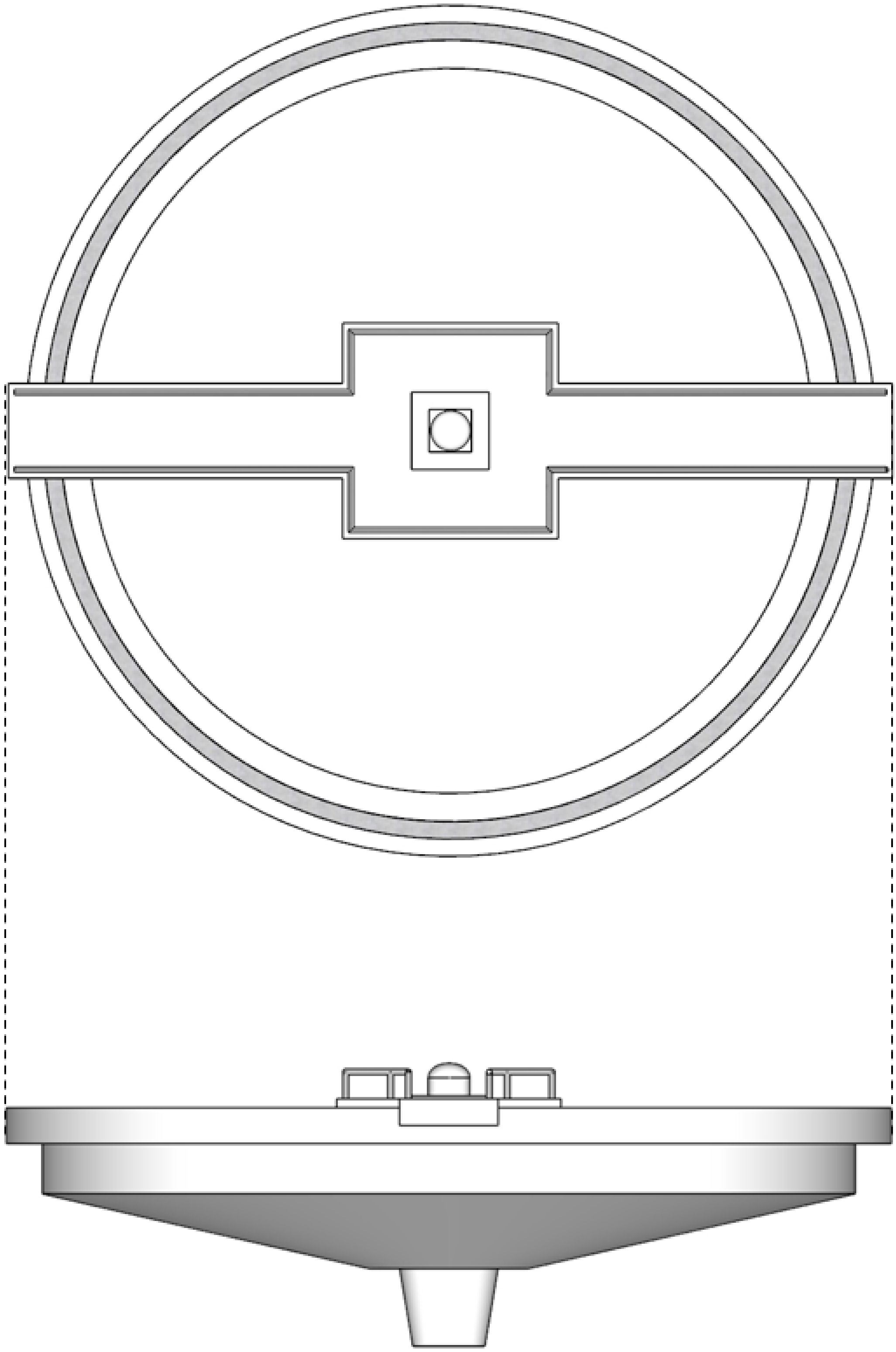

Figure 9. Multiview projection of the thickener

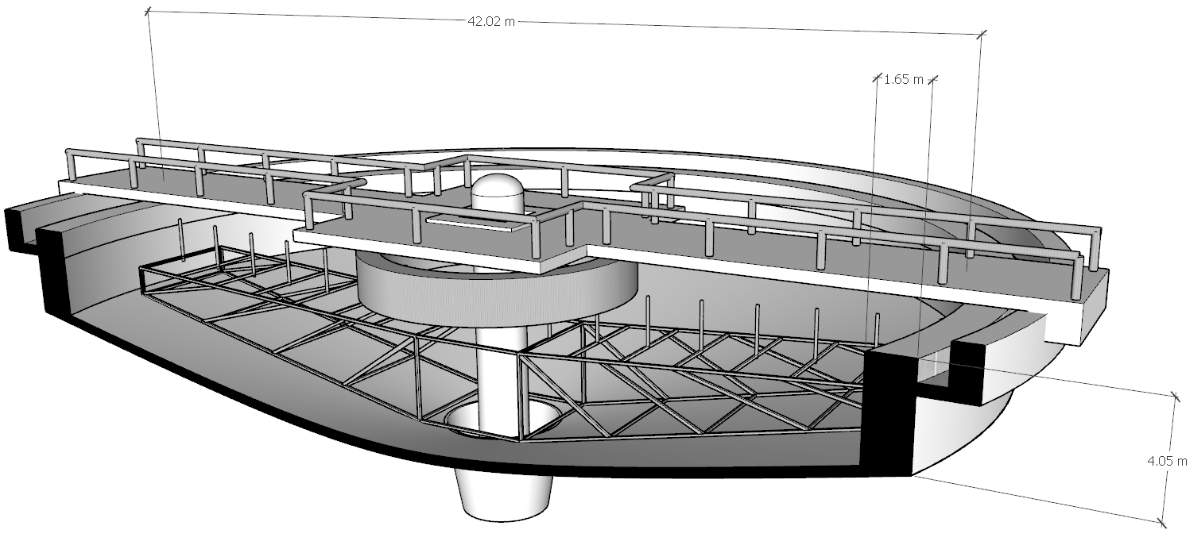

Figure 10. Isometric view of the cross-section of the thickener

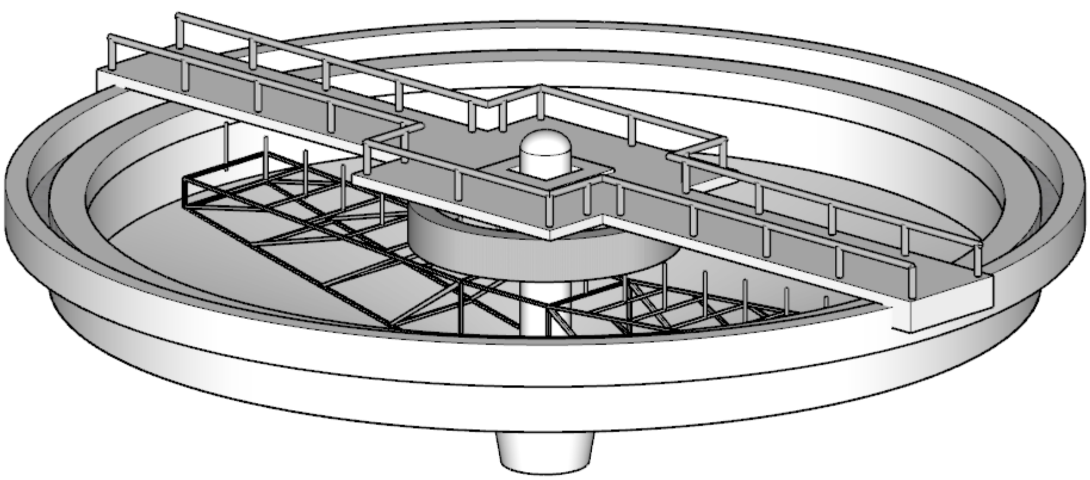

Figure 11. Isometric view of the thickener

References

Adhikari, Sukanta. (2018). Design tables for Liquid retaining structure as per IS 3370.

Chmielewski, R., Kruszka, L., & Muzolf, P. (2020). The selection of methods for strengthening of the reinforced-concrete structure of the open tank. *Case Studies In Construction Materials*, *12*, e00343. doi: 10.1016/j.cscm.2020.e00343

Eckenfelder, W.W., Melbinger, N. (1957). Settling and compaction of biological sludge, Sewage Ind. Wastes., 29:1114-1122.

Fattah-alhosseini, A., & Vafaeian, S. (2015). *Effect of solution pH on the electrochemical behaviour of AISI 304 austenitic and AISI 430 ferritic stainless steels in concentrated acidic media.* Retrieved from Research Gate: https://www.sciencedirect.com/science/article/pii/S1110062115000665

Green, D. and Southard, M. (2018). Perry's Chemical Engineers' Handbook 9th ed.

Kumar, M. M., Karthikeyan, R., Anbalagan, K., & Bhanushali, M. N. (2016). Coagulation process for tannery industry effluent treatment using Moringa oleifera seeds protein: Kinetic study, pH effect on floc characteristics and design of a thickener unit. Separation Science and Technology, 51(12), 2028–2037. doi:10.1080/01496395.2016.1190378

Parande, A., Ramsamy, P., Ethirajan, S., Rao, C., & Palanisamy, N. (2006). Deterioration of reinforced concrete in sewer environments. *Proceedings Of The Institution Of Civil Engineers - Municipal Engineer*, *159*(1), 11-20. doi: 10.1680/muen.2006.159.1.11

Samui, Pijush Kim, Dookie Iyer, Nagesh R. Chaudhary, Sandeep. (2020). *New Materials in Civil Engineering - 1.1.9 Reinforcing Bars.* Elsevier. Retrieved from https://app.knovel.com/hotlink/pdf/id:kt012LX275/new-materials-in-civil/reinforcing-bars

Talmadge, W., & Fitch, E. (1955). Ind Engg Chem. Ind Engg Chem, pp. 47:38-41.

Tarleton, E.S. (2007). Solid/Liquid Separation || Solid/liquid separation equipment. , (), 1–77. doi:10.1016/B978-185617421-3/50001-8

Towler, Gavin Sinnott, Ray. (2022). Chemical Engineering Design - Principles, Practice and Economics of Plant and Process Design (3rd Edition) - 18.6.2 Filtration.

Unit Operations of Particulate Matter. (2017a, July 3). Sedimentation and batch sedimentation test-1

Unit Operations of Particulate Matter. (2017b, July 3). Sedimentation and batch sedimentation test-2

Voutchkov, N. (2017). Introduction to Wastewater Clarifier Design.

Woodard & Curran, Inc. (2006). Methods for Treating Wastewaters from Industry. Industrial Waste Treatment Handbook, 149-334. doi: 10.1016/b978-075067963-3/50009-6