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Design Project 488 (2019)

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DOCUMENT-SET TABLE OF CONTENTS

1 INTRODUCTION AND PLANT OVERVIEW

The purpose of this document is to detail the plant control systems and philosophy as well as the valve and piping specifications.

The wastewater influent flows through the sump TK-101 to the buffer tank TK-102 after which it is heated to the temperature designated by the controller by effluent (if possible) and steam (heat exchanger E-101 and E-102 respectively). The CSTR anaerobic digester allows flow from the influent and recycle. The reactor effluent is removed of methane gas (TK-202), then solids are settled out in the clarifier V-202. The overflow heads off to the dewatering section (not shown). The sludge underflow is split into the waste stream and the recycled sludge stream.

2 SUPPORTING DOCUMENTS

The following supporting documents are identified and should be read in conjunction with this document:

Table 1: Supporting Documentation

Document	Drawing / Document Number
Piping & Instrumentation Diagrams	
P&ID for Buffer Tank and Feed Heating	Appendix B page 21
P&ID for Anaerobic Digester and Clarifier	Appendix B page 22
P&ID for pH Dosing Station	Appendix B page 23
Control Design Forms	
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3 CONTROL PHILOSPOHY - GENERAL

3.1 Control approach

The control system aims to clean the industrial effluent to allow for discharge to the environment while achieving the seven control objectives: maintaining the safety of personnel, protecting the environment protecting the equipment, maintaining smooth and easy operation, maintaining product quality, maintaining a high efficiency and allow for monitoring and diagnosis.

Examples of achieving the control objectives are as follows: Personnel safety is achieved through ensuring no tank overflows or any significant pressure build-up in the digester. Environmental protection is achieved through flaring excess methane. Equipment is protected through low level interlocks which protect the centrifugal pumps from running dry and subsequently cavitating. Smooth and easy operation is achieved through the buffer tank TK-102 which ensures constant flow. Product quality is maintained through the clarifier sludge recycle loop which enables the SRT to be adjusted as necessary. Efficiency is maintained through the sludge recycle system. Measuring and recording the methane composition in the biogas line allows for the quality of the digestion process to be quantified and compared to previous data.

3.2 Control Term Definitions

H and L - high and low alarms, respectively. For when the measured variable is high and low respectively. An alarm that the operator can see and hear will occur. The alarm will continue until action is taken to rectify the issue or the alarm is turned off.

HH and LL – high and low triggered interlocks. These occur when the variable is high or low enough to automatically trigger and interlock. The controller visually and aurally notifies the controller that an interlock has been triggered. The alarm is less noisy and has a different sound compared to the H and L alarms. It is turned off once the controller acknowledges the change in process conditions.

Direct/reverse acting controller – considering only the CV and the FCE: if your CV has a positive error and your controller takes action to mitigate the error by opening the valve, it is a direct acting controller. If the FCE element decreases to compensate for a positive error in the CV it is reverse acting.


Knife gate valve - a form of a gate valve specifically designed to cut through slurry and viscous liquids.


Interlock activated by a HH alarm being tripped.


Interlock activated by a LL alarm being tripped.

3.3 Defined control modules

Table 2: Control Modules

	Control Module	Major Equipment Included	Control Description
1	Buffering Feed Sump <> P-102 A/B	TK-101 Feed Sump TK-102 Buffer Tank P-101 A/B Buffer tank feed pumps P-102 A/B Reactor feed pumps	The solids are kept in suspension using a mixer running at a constant speed in the buffer tank. Level control with interlocks ensure that no overflow or dry running occurs in the sump or buffer tank by switching off a pair of pumps or preventing overflow through draining the excess to the calamity tank.
2	Pre-heating Process Effluent Heating heat exchanger <> Steam Heating	E-101 Process Effluent Heating E-102 Steam Heating	The influent is heated to the design temperature. The wastewater effluent is used to heat the influent as much as possible to reduce the amount of steam being used. If this heating is not possible the effluent heating valve is shutoff completely. The steam flowrate is

			controlled to ensure that the reactor temperature is within the design range.
3	Digesting Anaerobic Digester <> Degasser	R-201 Anaerobic Digester P-201 A/B Reactor Overflow Pumps P-202 A/B Reactor Mixing Pump TK-202 Degasser	Interlocks are used to ensure that no overflow to the biogas section occurs in the digester. The flow overflows out the digester at a set flowrate due to the outlet position and the constant flow pumps. Control is used to ensure that the tank never exceeds the pressure upper limit.
4	Clarification Clarifier <> Recycle Pumps	V-111 Clarifier TK-201 Underflow Sump P-204 A/B Recycle Pumps	The reactor effluent flows into the clarifier. The interlocks are used to ensure no overflow or dry running of the clarifier occurs by controlling the pumps. The recycle ratio is adjustable by using a variable speed drive.
5	Dosing Slaked lime hopper <> Dosing mixing tank	V-101 Slaked lime hopper SC-101 Screw conveyor P-101 A/B Process effluent water for lime slurry V-102 Dosing mixing tank	Ratio control is used to keep the approximate concentration of the slurry in the mixer within an acceptable range. Interlocks are used to ensure that the mixing tank does not overflow.

4 CONTROL PHILOSOPHY – PER MODULE

4.1 Buffering

4.1.1 Operating philosophy

Equipment:

- TK-101 Feed sump tank
- P-101 A/B Buffer tank pump
- TK-102 Feed buffer tank
- P-102 A/B Reactor feed pump
- E-101 Effluent heating heat exchanger
- E-102 Steam heating heat exchanger

Tank TK-101 is drained by pump P-101 A at a constant flowrate. The level controller (LIC-101) measures the level of the sump. If the level is low an alarm (L) is triggered. This alarm is necessary as it alerts the operator that all the downstream processes will be without a feed. If it gets any lower the low-low (LL) interlock is triggered which stops the pump P-101 A. When the level triggers the HH interlock, the valve to the calamity tank (LCV-102) is opened and the excess is drained. No H alarm is used as too much influent will not disrupt the process downstream and is just pumped back into the system when the influent flowrate is below the nominal design flowrate.

A hand valve (HV-101) can be manually operated to drain the influent sump to the calamity tank.

Due to the solids presence of solids influent blockages are possible. Pressure release valves (PRV-101 and PRV-102) allow for the release of liquid should a blockage occur. This will prevent pipes from bursting. The pressure release valve is used after every pump. The pump also has a drain valve attached (HV-103 and HV-104).

TK-102 is mixed at a constant rate by the agitator operated by an onsite hand-switch and a hand-switch available to the controller (this is true for all mixers in the plant). If methanogenisis reactions do occur

VT-101 will flare it to prevent dangerous pressure build-up and environmental damage. HV—108 can be manually used to drain the contents to the calamity tank. Level controller LC-102 monitors the level and controls the outflow of the pumps P-102 A/B by using a throttling valve. The controller uses non-linear averaging level control to keep the flow constant (the level has a set-point (SP)), but is allowed to deviate within an acceptable range). The flow is the secondary loop in the cascade level control (FIC-101). A LL interlock automatically turns off the outlet pumps P-102 A/B to prevent completely draining TK-102. The HH interlock stops P-101 A/B from feeding any more wastewater.

P-102 A/B (drain valves HV-110 and HV-113 and pressure release valves PRV-103 and PRV-104). Run at a constant flowrate.

Controller TIC-101 reads heat exchanger (E-101)'s influent temperature and sends the data to TIC-102 which also reads the temperature of the effluent stream. If the effluent stream is higher than 10^{O}C of the wastewater stream, valve TCV-101 will be completely open else it will be closed completely.

Heat exchanger E-102's steam flowrate is controlled via cascade control. The temperature of the reactor is measured (it has a slow response) and sent to controller TIC-103 (the primary loop). The temperature is sent as a set point to TIC-104 with the reading of the temperature of the liquid in the line directly before the inflow to the digester (this element is placed as close to the input port of the reactor as possible get an accurate reading of the temperature of the liquid flowing into the reactor). This is the secondary loop. This controller adjusts the amount of steam being used to heat the stream via valve TCV-102. TIC-103 has an H and L alarm for when the temperature deviates moderately from the SP.

The pumps (P-101 A/B, P-102 A/B and TK-102's mixer) will have the following status allocation, which can be changed from the SCADA:

- "Duty"
- Stand-by"

4.1.2 Sequences

4.1.2.1 Start-up Sequence

Inflow from the plant needs to start to flow. TK-101 and TK-102 to be drained and cleaned and ready to receive feed.

- TK-102's mixer is set to "Duty".
- The feed is started when TL-101 and TK-102 are able to receive feed (HV-108 and HV-127 is closed).
- TK-101 is allowed to fill to a point where interlocks or alarms will not be triggered.
- HV-102 is opened as well as HV-103. Once liquid starts flowing out HV-102 (gas is purged and the volute is filled) is closed.
- HV-104 (pump discharge valve) is opened by an eighth. P-101 A is set to duty and allowed to run until steady operation
- HV-104 is fully opened. LIC-101 is activated (CV-101 prevents backflow).
- HV-109 and HV-110 are opened until liquid flows out.

- Since this pump has a high speed HV-111 is opened along with HV-115 and HV-117.
- Once the level in TK-102 is within a range that will not trigger any interlocks. P-102 A/B is set to duty.
- Controller LIC-102 is activated TCV-101 opened to 30% open over 10 seconds. When the valve is 30% opened the controller (PI) starts to control the valve.

4.1.2.2 Shutdown Sequence

- LIC-102 is stopped by closing valve LCV-101 from %open to 0% in over 20 seconds.
- Discharge valve HV-111 is closed.
- P-102 A is set to standby
- HV-109 is closed
- HV-104 is closed
- LIC-101 is shut off by switching P-101 A to standby
- HV-102 is closed.
- TK-102 mixer is stopped and HV-108 is used to train it to the calamity tank.
- The line can be drained by closing HV-115 and HV-117 and opening HV-116, HV-110, HV-113, HV-108, HV-106 and HV-103.

4.1.3 Process and Safety Interlocks

Description	Process Interlock	Safety Interlock
P-101 A/B Duty	LIC-101 < LL	LIC-102 > HH
LCV-102	N/A	LIC-101 > HH
P-102 A/B Duty	LIC-102 < LL	LIC-201 > HH

4.1.4 Loop descriptions

4.1.4.1 Sump Tank (TK-101) Level Controller (LE-101)

Range: 0 – 8m

Set Point: 6.5 (adjustable in SCADA)

Action: Reads level of tank (MV). If it is high or low enough it can trigger an interlock which alters the flow (MV). Triggering the HH interlock controls the LCV-102 FCE and triggering the LL interlock controls P-101A FCE. On-off control is used.

4.1.4.2 Buffer Tank (TK-102) Level controller (LE-102)

Range: 0 – 3.5 m

Set Point: 2 m (adjustable in SCADA)

Action: Reads tank level (CV). The controller uses non-linear averaging level control using a PI controller to ensure a constant flow (flow is the MV). This is the primary loop. The secondary loop accepts the SP from the primary controller. It measures the flow out of the tank and adjusts the throttling valve accordingly. The controller is direct acting.

The proportional term will be weak for both small deviations, as fast dynamic correction of the level is not important. Large deviations from set-points will have a slightly more aggressive response. The integral action serves to get the level within the acceptable range, zero-steady state offset is not a priority, therefore integral action is not aggressive.

LL puts P-102 A (FCE) to stand-by and HH sets P-101 A (FCE) to stand-by.

4.2 Pre-Heating

Equipment:

- E-101 - Effluent heating heat exchanger
- E-102 – Steam heating heat exchanger

This module controls the heating of the inflow stream to the reactor R-201. TIC-101 reads the temperature of the wastewater stream and TIC-102 the effluent. An interlock (it closes the valve) is activated if the effluent stream is not at least 10°C greater than the influent stream.

Reactor temperature is controlled via cascade control. TIC-103 (which makes up the primary loop) computes and displays the temperature of the reactor and sends the SP to TIC-104 (the secondary loop) which measures the temperature of the influent just before it enters the digester R-201. TCV-102 makes up the FCE and is controlled to adjust the heating delivered to the stream.

4.2.1 Sequences

4.2.1.1 Start-up Sequence

The steam utility needs to be made available. Influent needs to flow into the module with an acceptable flowrate.

- TCV-102 is opened to 30% in over 20 seconds.
- This activates the PI controller TIC-104 which takes control of the valve.
- The cascade controller TIC-103 is then started
- Once flow exits the clarifier as effluent to the discharge point TCV-101 can be opened from 0% to 30% open which activates TIC-102.
- This intern activates primary cascade controller TIC-101.

4.2.1.2 Shutdown Sequence.

- TIC-104 is turned off by closing TCV-102 from %0 open to 0% over 20 seconds.
- Primary loop cascade controller TIC-103 is thus switched off.
- TIC-102 is turned off by completely closing TCV-101 in over 20 seconds.
- This will turn TIC-101 off
- Heat exchangers are drained using HV-120 and HV-125.

4.2.2 Process and Safety Interlocks

Description	Process Interlock	Safety Interlock
TCV-101	TE-102 -10°C ≤ TIC-101	N/A

4.2.3 Loop descriptions

4.2.3.1 Effluent Heating Heat Exchanger (E-101) Controller TIC-102 and TIC-101

Range: $10^{O}C$ to $40^{O}C$

Set Point: N/A

Action: Open the FCE TCV-101 if TE-102 reads at least $10^{o}C$ greater than TE-101, else it is completely closed.

4.2.3.2 Steam Heating Heat Exchanger (E-102) Temperature Controllers (TIC-104) and (TIC-103)

Range: TE-103A: $20^{O}C$ – $50^{O}C$; TE-103B: $30^{O}C$ – $37^{O}C$; TE-104: $20\,^{O}C$ -$40^{O}C$

Set Point: $36^{O}C$

Action: TE-103A and TE-103B measure the temperature and this is sent to TIC-103. This is the primary loop. The SP from this controller is sent to TIC-104 which also reads the reactor influent temperature. The primary controller TIC-103 uses a PI algorithm as the primary variable needs to achieve zero steady-state offset.

The controller is reverse acting as decreasing the FCE (the valve area) is necessary to TIC-104 also uses PI control even though it does not require zero steady-state offset because it improves the effectiveness of the control without much drawbacks due to the secondary loop being much faster than the primary.

4.3 Digesting

4.3.1 Operating philosophy

- R-201 Anaerobic Digester
- P-201 A/B Reactor Overflow Pumps
- P-202 A/B Reactor Mixing Pump
- TK-202 Degasser

This module controls the flow out of the anaerobic digester R-201 while maintaining an acceptable level. LE-201 transmits the level to LT-201 then to LIC-201 which has a HH interlock that shuts off the lime dosing pumps (P-301 A/B) and the reactor feed pumps (P-102 A/B) to prevent overloading into the biogas line should it be triggered. ARC-201 monitors and records the biogas composition. This is a good indication of the state of the process. The recording allows for trends to be estimated and performance to be predicted (Schuyler, 2013).

P-202 A/B are positive displacement pumps that run at a constant flowrate (as they extract the digester overflow) the interlock used on them are if the clarifier overflows. P-201 adds extra mixing to the reactor in the form of a draft tube in addition to the agitator.

PIC-201 measures the pressure at the base of the conical section of the digester. It has an H alarm and HH interlock which will open the control valve PCV-201 to the calamity tank if triggered.

COD and TOC are measured in the laboratory using HV-215 to sample.

The pumps (P-202 A/B, P-201 and R-201's mixer) will have the following status allocation, which can be changed from the SCADA:

- "Duty"
- Stand-by"

4.3.2 *Sequences*

4.3.2.1 Start-up Sequence

Flow needs to flow with an acceptable flow and pressure. R-201 needs to be ready for the influent. The anaerobic digester mixer needs to be operational.

- R-201's mixer is set to "Duty".
- HV-204 is made sure to be open and HV-203 is confirmed close.
- Since no LL interlocks or L alarms exist on LIC-201 it can be switched on while the reactor fills.
- HV-219 is opened HV-220 is opened until liquid exits.
- HV-221 is opened and P-202 A is set to "Duty".
- HV-205 is opened and HV-206 is opened until liquid exits.
- HV-207 is opened and P-201 is set to "Duty".
- AE-201 is switched on.

4.3.2.2 Shutdown Sequence

- P-201 and R-201's mixer are set to "stand-by"
- HV-207 and HV-205 are closed in that order
- HV-206 drain any remaining liquid in the pump
- P-202 is set to "stand-by"
- HV-221 and HV-219 are closed
- P-202 A is drained via HV-220.

4.3.3 *Process and Safety Interlocks*

Description	Process Interlock	Safety Interlock
PCV-201	N/A	PIC-201 > HH
P-302 A/B Duty	LIC-201 > HH	N/A
P-102 A/B Duty	LIC-201 > HH	N/A

4.3.4 *Loop descriptions*

4.3.4.1 Anaerobic Digester R-201 Pressure Controller PIC-201

Range: 0 – 1000 kPa
Set Point: No SP just interlock if it exceeds 450 kPa
Action: If the pressure (CV) reading exceeds 450 kPa the interlock activates and opens the control valve PCV-201 (FCE) i.e. it works using on-off control. The MV is the flow of liquid drained from the digester.

4.3.4.2 Anaerobic Digester R-201 Level Controller LIC-201

Range: 0-18 m

Set Point: 12 m (adjustable in SCADA)

Action: the level (CV) is stopped from overflowing by the level controller LIC-201 interlock (with preceding alarm).

4.3.4.3 Biogas Line Methane Analyser (ARC-201)

Range: 0-100%

Set Point: N/A

Action: None apart from recording.

4.4 Clarification

4.4.1 Operating philosophy

Equipment:

- V-111 Clarifier
- TK-201 Underflow Sump
- P-204 A/B Recycle Pumps

This control module takes in the flow from the degasser into V-202 the thickener. Level controller (LIC-201) with HH and LL interlock which stops P-202 A and P-203 A, respectively. The controller also has H and L alarms to alert the operator in case of over flow or dry running. The level element measures the level of the outer ring (the overflow weir). FIC-201 controls the amount of sludge being recycled back to the reactor (thus affecting the SRT) and how much sludge gets wasted through the centrifuge by varying the variable speed drive (VSD)[1]. The recycle and total sludge flowrate leaving the clarifier are both measured and displayed. The ratio is controlled as the price of selling the dewatered sludge will vary depending on building projects in the area. It may be more economically feasible to waste more sludge at a later date and the controller allows you to change it.

TIC-201 has LL and HH interlocks to shutoff the recycle pumps if the temperature is so far off from the digester SP that it cannot be rectified by the steam heating heat exchanger.

The pumps (P-203 A/B and V-202's Mixer) will have the following status allocation, which can be changed from the SCADA:

- "Duty"
- Stand-by"

[1] A VSD is used as positive displacement pumps cannot be controlled using a throttling valve and the alternative method of control (a kick-back line) is not possible as it will unnecessarily disturb the clarifier.

4.4.2 Sequences

4.4.2.1 Start-up Sequence

TK-201 and TK-201 need to be ready for influent. V-202 needs to be ready and the mixer needs to be operational.

- V-202’s mixer is switched to “Duty”
- Once the level in the clarifier (V-202) is between the interlock percentages LIC-201 is switched on.
- HV-210 is opened and HV-209 is opened until liquid exits.
- HV-208 is opened and P-203 A is switched to “Duty”
- Once the TIC-201 has a reading that will not trigger the interlock it is enabled.

4.4.2.2 Shutdown Sequence

- V-202’s mixer is switched to “Stand-by”
- Level controller LIC-201 is turned off
- P-203 A is switched to “Stand-by”
- HV-208 is closed followed by HV-210
- HV-209 is opened to drain P-203 A
- HV-205 is opened to drained HK-201.
- HV-222 is opened to drain V-202.

4.4.3 Process and Safety Interlocks

Description	Process Interlock	Safety Interlock
P-202 A/B	N/A	LIC-201 > HH
P-203 A/B	TIC-201 > HH TIC-201 < LL LIC-201 < LL	N/A

4.4.4 Loop descriptions

4.4.4.1 Clarifier (V-202) Level Controller (LIC-202)

Range: 0-6 m

Set Point: 5.4 m

Action: if HH is triggered the feed pumps P-202 A/B (FCE) are shutoff, thus stopping the MV (flowrate). If it gets too low and the LL is triggered the draining pumps P-203 A/B (FCE) are stopped. The level is the CV. This system (while debatable whether it is necessary or not) prevent the overflow from flooding into the environment. This ensures the safety of the personnel is safeguarded.

4.4.4.2 P-203 A/B VSD Controlled by Flow Controller FIC-201

Range: 0 – 30 m^3/hr

Set Point: 11% recycle ratio

Action: The ratio (CV) is calculated using the readings obtained from FE-201 and FE-202. The recycle to the digester is altered (MV) by changing the VSD (FCE). PI control is used as zero steady-state offset is required to achieve the desired ratio. [2]

4.4.4.3 P-203 A/B and Temperature Control Interlock

Range: $15^{O}C – 40^{O}C$

Set Point: N/A

Action: Shuts off the pump P-203 A/B if the temperature is surpasses HH or dips below the LL value.

4.5 Dosing

4.5.1 Operating philosophy

Equipment:

- V-101 Slaked lime hopper
- SC-101 Screw conveyor
- P-101 A/B Process effluent water for lime slurry

This module controls the amount of calcium hydroxide that will flow into the digester. The concentration of the mixture is controlled by FIC-301 using FCV-301 to control the flowrate of water. The level controller LIC-301 uses interlocks to stop the feed pump P-301 A/B and screw conveyor SC-301 if the HH interlock is tripped. P-302 A/B is tripped by the LL interlock.

AIC-301 reads the pH from the digester R-201. Depending on the reading the control valve ACV-301 position is changed. The control valve changes the flowrate of the kickback line to V-301 which additionally provides extra mixing to V-301.

P-301 A/B, SC-301 V-301’s mixer and P-302 A/B have two states, which can be changed from the SCADA:

- “Duty”
- Stand-by”

4.5.2 Sequences

4.5.2.1 Start-up Sequence

The influent needs to flow with an acceptable flowrate. The tank needs to be ready for inflow V-302.

- V-301’s mixer is switched to duty
- HV-304 is opened with HV-306.
- Once liquid fills the volute of P-301 A and flows out of HV-306, HV-306 is closed.
- P-301 A is set to “Duty”
- SC-301 is switched to “Duty” with no lime added yet
- FIC-301 is enabled.

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[2] The other pump is in the dewatering section and ensures controlled flow to the respective modules.

- FCV-301 is opened from 0% to 20% over 10 seconds which allows FIC-301 to control the valve
- HV-311 is opened
- Once V-301 fills up to a level that will not trigger the LIC-301 interlock the controller is switched on.
- AIC-301 is switched on
- ACV-301 is opened from 0% to 20% over 10 seconds which allows AIC -301 to control the valve
- Now slaked lime can be loaded into V-302.
- HV-312 is opened until liquid starts flowing out then it is closed.
- P-302 A/B is switched to “Duty”
- HV-313 is opened.

4.5.2.2 Shutdown Sequence

- P-302, V-302’s mixer and SC-301 is set to “stand-by”
- HV-311 is closed followed by HV-313
- AIC-301 is stopped by closed in ACV-301 completely in 30 seconds.
- FIC-301 is switch off by closing FCV-301 completely in over 20 seconds
- HV-305 is closed
- P-301 is set to stand-by
- HV-304 is closed.

4.5.3 Process and Safety Interlocks

Description	Process Interlock	Safety Interlock
SC-301	LIC-301 > HH	N/A
P-301 A/B	N/A	LIC-301 > HH
P-302 A/B	LIC-301 < LL	N/A

4.5.4 Loop descriptions

4.5.4.1 Ratio Controller FIC-301

Range: FE-301: 0 m^3/h – 10 m^3/h

Set Point: 350 times more water than calcium hydroxide.

Action: FE-301 reads the flowrate of the liquid and compares it to the constant flow of the calcium hydroxide. The FCE (FCV-301) is changed (which changes the MV, the flowrate) so that the ratio (CV) is within an acceptable limit (exact ratio is not required, just ensure that it lies within the accepted limits).

4.5.4.2 pH control AIC-301

Range: 6.8 to 7.2

Set Point: 7

Action: AE-301 reads the pH (CV) and alters the flowrate of calcium hydroxide (MV) to the digester to achieve this value by changing the position of the FCE (ACV-301). This controller utilizes PI control to achieve zero steady-state offset.

4.5.4.3 V-302 Level Controller (LIC-301)

Range: 0 – 4 m

Set Point: 3.8 m
Action: the controller triggers HH and LL interlocks. HH halts SC-301 and P-301 A/B while the LL interlock stops P-302 A/B.

5 PROCESS UNIT DESIGN CONSIDERATIONS

5.1 Reactor feed pump – P-102 A/B

The pump selected for this is the horizontal single stage centrifugal pump. Although the influent contains solids which will impact and wear the impeller, it has the advantage of being cheaper, easier to control the flowrate and more efficient than positive displacement pumps (Lakeside Equipment Corporation, 2018). The solids content is low enough (under 2%) for the impeller damage to be mitigated through the appropriate material selection and impeller type selection. Additionally, blockages that may occur will not damage the pipe or pump. The centrifugal pumps are also more compact than positive displacement ones.

(Water World, 2014) promotes the use of nickel-aluminium-bronze (N-A-B) as it has the highest life factor of the materials commonly used for pump impellers. (Morrow, 2010) shows that N-A-B has an overall lower cost than duplex stainless steel while providing better corrosion resistance (in the form of pitting than stainless steel 316) provided no hydrogen sulphides are present in the influent.

The casing was selected to be cast iron due to its inexpensive nature and due to the casing being easy to remove and replace.

Semi-open impeller is used due to it being able to handle suspended solids, (PetroWiki, 2017) with a backward vane impeller to maximize efficiency (due to the incompressible nature of the fluid) (PTOA, 2017).

5.2 Feed steam heat exchanger – E-102

The plate and frame heat exchanger is ideal for heat exchangers requiring expensive materials due to its low total area when compared to its alternatives such as the shell and tube heat exchanger (Thermex, 2018). The double pipe heat exchanger is more compact but is limited to low heating requirements only. The wastewater does contain a fraction of solids (albeit low), this will result in fouling. The shell and tube heat exchanger fouls less, therefore is ideal for this application (Sinnott, 2005). Not only will the heat exchanger require less frequent maintenance, but more solids will be available for digestion.

The plate and frame heat exchanger has a lower approach temperature, which means (in this case) the steam will have to be heated to a lower temperature to adequately heat the influent stream to the SP. It also allows for easy expansion if needed.

To resist corrosion stainless steel 316 was used and are used in wastewater treatment plants (Montanstahl, 2017). This grade of stainless steel also has a high thermal conductivity than more corrosive options such as duplex stainless steel (ASM, 2019).

5.3 Clarifier – V-202

Circular clarification tanks are more economical to build than their rectangular counterparts while still having a large efficiency (Crittenden et al., 2012). It does take up more ground space than rectangular clarifiers do (due to the fact that they can share a common wall). It is easier to remove sludge off the bottom of the circular clarifier than the rectangular clarifier. This form of clarifier is sensitive to shock loads, however (shock loading is not at all common in this plant).

Horizontal loaded clarifiers have a complicated sludge removal mechanism. Sludge has a higher tendency to get stuck in corners of the vessel (Crittenden et al., 2012).

A centre loaded clarifier allows for an even distribution of influent. This setup also prevents short-circuiting which is common in horizontal loaded circular clarifiers.

Therefore, due to the above points, the circular clarifier with centre loading was selected. Concrete was selected as the clarifier material of construction (calculated to be 15cm thick wall and base that is 20cm thick). Only 1 metre of the clarifier will be above ground, therefore thinner concrete can be used as some of the load will be distributed to the foundation. Concrete (in this case C25/30 as per recommendation by (Nosive Strukture, 2017)) is cheap and appropriate for this use as the only requirement is that the clarifier hold the fluid.

The rake is constructed out of stainless steel 316 with rubber contacting with the bottom of the clarifier. A highly corrosive resistant material is required due to the high concentration of solids at the bottom of the clarifier.

The driver of the rake is housed in cast iron. A spur gear motor was selected as it provides the option of high torque if required unlike the worm gear motor (which is quieter) which is limited in that respect (Difference Box, 2017). The actual gear is constructed of stainless steel 304. The launder is constructed out of concrete.

5.4 Sludge recycle pump – P-203 A/B

The pump used here is a positive displacement pump. This is due to the percentage of solids being roughly 5%. The sludge here is recycled back into the reactor, therefore it is required that the shear be low to prevent microbial death (Engineered to Work, 2017). Centrifugal pumps impart a high amount of shear which is detrimental to the microorganisms in the sludge (LobePro, 2017).

The diaphragm pump is economical option, however its operation is greatly hindered by solids. The progressive cavity pump can handle solids and has low shear, but this is offset by the high cost and complicated maintenance (LobePro, 2017).

The rotary lobe pump has a low footprint, low shear and is not expensive (Engineered to Work, 2017). This pump lobe can easily be changed if necessary which ideal for a highly corrosive transport fluid (Engineered to Work, 2017). It can handle both viscous and non-viscous fluids unlike most other pumps (LobePro, 2017).

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APPENDIX A – REACTOR CONTROL DESIGN FORM

Title:	Anaerobic Digester R-201	Organization:	Stellenbosch University
Unit:	Distell	Designer	V.V. Raga
Drawing:	2	Date	15 September 2019

Control Objectives

1. Safety of personnel
    a) The pressure should not exceed 400 kPa at any point in the reactor under any circumstances.
    b) An emergency drain valve is provided to prevent tank rupture. It should not be utilized more than four times a year
    c) A pressure relief valve is provided to prevent pipeline rupture. It should not be activated more than once a day.
    d) Service hatch should not be accessible if mixer is set to duty
    e) Ignition sources should remain far away from digester headspace.
2. Environmental Protection
    a) Excess gas is sent to the flare, never to the atmosphere (methane).
    b) An emergency drain valve is installed to the calamity tank to prevent environmental pollution (this should never occur).
3. Equipment Protection
    a) The pressure should not exceed 400 kPa at any point in the reactor under any circumstances.
    b) Liquid should not enter the biogas line ever
    c) Solids should not settle out in the digester more than once a year
    d) No foaming should occur more than 2 times a year. Dosing with ferric chloride will prevent this
4. Smooth, easy operation
    a) Control all unstable variables (liquid level, outlet flowrate and turbidity)
    b) Mixing should be rigorous enough to prevent solids from settling.
    c) All process variables should remain within a reasonable range without undue operator actions.
    d) Control loops should function well independent of manual/automatic status of other loops.
    e) Alarms should not be triggered more than twice a day
    f) One variable should control the production rate without much variation.
    g) The digester should be sufficiently mixed so that the pH and temperature is uniform throughout the volume.
5. Product quality
    a) The solids retention time should high enough (designed for 22 days) so that the methanogenic conversion capacity of the sludge is maintained. This is achieved through recycle and varying the recycle ratio.
    b) The hydraulic retention time should be 17 hours to allow for full biological conversion.
    c) To ensure the correct HRT and SRT the volume of liquid in the digester should be around 4600m^3 as per the design.

d) The temperature should be kept around 35^{o}C to ensure suitable anaerobic growth and thus digestion. It should not change more than 0.6^{o}C per day.
e) pH needs to be kept at 7 to ensure sufficient microbial growth and conversion. This mixing is achieved through the agitator and the recycle from the positive displacement pump.
f) To ensure the correct pH (7) for all liquid in the reactor, the digester needs to be perfectly mixed.

6. Efficiency and optimization
   a) Process integration is used to decrease the energy requirement through the use of steam from the process water.
   b) The mixing is controlled to ensure uniform pH and temperature to prevent pH and temperature gradients, thus optimize microbial activity and digestion.
   c) The recycle ratio should be controlled
7. Monitoring and diagnosis
   a) Sensors and displays needed to monitor the normal and upset conditions of the unit are provided to the plant operator
   b) Calculated variables required to monitor and diagnose the temperature and solids content are available and recorded.
   c) Important measurements are available on the field.

Measurements

Variable	Sensor Principle	Nominal value and sensor range	Special information
TE-103A	Thermistor	36^{o}C, 20^{o}C -50^{o}C	
TE-103B	Thermistor	36^{o}C, 30^{o}C -40^{o}C	*Takes priority over TE-103A when TE-103B is within the sensor range.*
LE-201	Conductivity level sensor	11.4m, 0m-20m	
PE-201	Piezoelectric	191 kPa, 101 kPa-500 kPa	
AE-301	pH	7, 6-8	

Manipulated Variables

I.D.
Wastewater Flowrate
Buffer Flowrate
Temperature

Constraints

Variable	Limit Values	Measured / Inferred	Hard / Soft	Penalty for Violation
Digester Pressure	382 kPa and 101kPa (abs)	PE-201 Measured	Hard	Reactor damage/ digester rupture. Personnel injury. Environmental pollution.
Digester Temperature	37^{o}C and 33^{o}C	TE-103A T-103B Measured	Hard	Acidification. Subpar product quality and gas production. Microorganism death.

Level	80%	LE-201 Measured (on-site)	Soft	Liquid in the gas line. Need to drain the line after shutoff. Loss of methane gas production. May result in equipment damage.
Methane in the liquid outlet line	Negligible (degassifier prevents this)	Inferred	Soft	Lowering of effluent flowrate. Loss of biogas that can be sold/used for heating.

Disturbances
Digester Feed Temperature Feed Composition Micronutrients Concentration

APPENDIX B – PIPING AND INSTRUMENTATION DIAGRAMS

APPENDIX C – PIPING SCHEDULE

PVC was used due to its cost effectiveness and very low friction factor. CPVC is used for areas that are at risk of causing the pipe temperature to exceed 60^{O}C (worst case scenario). The insulation is ideal for PVC pipes that need to retain their temperature after being heated, but before entering the digester.

Table C: Piping schedule

Line number	Size (mm)			Process Fluid	Material	Class / Schedule	Temperature (°C)		Pressure (bar(a))		Flow (m^3/h)	Velocity (m/s)
	DN	OD	ID				Operating	Design	Operating	Design		
101	63.5	73.03	62.10	Influent Wastewater	PVC	40	17	60	1.1	20.69	58.75	5.39
102	63.5	73.03	62.10	Influent Wastewater	PVC	40	17	60	1.1	20.69	58.75	5.39
103	63.5	73.03	62.10	Influent Wastewater	PVC	40	17	60	1.3	20.69	58.75	5.39
104	63.5	73.03	62.10	Influent Wastewater	PVC	40	17	60	1.6	20.69	58.75	5.39
105	63.5	73.03	62.10	Influent Wastewater	PVC	40	17	60	1.6	20.69	58.75	5.39
106	76.20	88.90	72.75	Influent Wastewater	PVC	80	17	60	1.6	25.51	58.75	3.93
107	76.20	88.90	72.75	Influent Wastewater	PVC	80	17	60	2.8	25.51	58.75	3.93
108	76.20	88.90	72.75	Influent Wastewater	PVC	80	17	60	2.6	25.51	58.75	3.93
109	76.20	88.90	72.75	Influent Wastewater	CPVC	80	19	60	2.5	25.51	58.75	3.93
110	76.20	88.90	72.75	Influent Wastewater	CPVC & CGI	80	36	90	2.4	25.51	58.75	3.93
111	76.20	88.90	72.75	Influent Wastewater	CPVC & CGI	80	17	90	2.4	25.51	58.75	3.93
112	76.20	88.90	72.75	Influent Wastewater	CPVC & CGI	40	17	90	2.4	25.51	58.75	3.93
113	63.50	73.03	62.10	Influent Wastewater	PVC	40	25	60	1.6	20.69	58.75	5.39
114	63.50	73.03	62.10	Influent Wastewater	PVC	40	25	60	1.6	20.69	58.75	5.39
115	63.50	73.03	62.10	Influent Wastewater	PVC	40	23	60	1.5	20.69	58.75	5.39
116	63.5	73.03	62.10	Influent Wastewater	PVC	40	140	60	4	20.69	58.75	5.39
117	63.5	73.03	62.10	Influent Wastewater	PVC	40	139	60	2.3	20.69	58.75	5.39
201	76.20	88.90	72.75	Reactor Effluent	PVC	80	36	60	1.3	25.51	75.3125	5.03
202	76.20	88.90	72.75	Reactor Effluent	PVC	80	36	60	1.3	25.51	75.3125	5.03
203	76.20	88.90	72.75	Reactor Effluent	PVC	80	36	60	1.3	25.51	75.3125	5.03
204	88.90	101.60	58.17	Clarifier Underflow	PVC	80	30	60	1.6	25.51	16.24	1.70
205	88.90	101.60	58.17	Clarifier Underflow	PVC	80	30	60	1.5	25.51	16.24	1.70
206	63.5	73.03	62.10	Sludge Overflow	PVC	40	25	60	1.1	20.69	59	5.20
207	31.75	42.16	31.88	Sludge Recycle	PVC	80	29	60	2.7	35.85	14.65	5.10
208	31.75	42.16	31.88	Sludge Recycle	PVC	80	27	60	2.7	35.85	14.65	5.10
209	9.53	21.34	13.36	Dewatering Sludge	PVC	80	22	60	2.7	58.61	2.28	4.52

210	38.10	48.26	37.49	Sludge Recycle	PVC	80	25	60	2.7	32.41	16.93	4.26
211	50.80	60.33	48.59	Draft Tube Recycle	PVC	80	36	60	2.7	27.58	26.71	4.00
212	31.75	42.16	31.88	Sludge Recycle	PVC	80	29	60	2.2	35.85	14.65	5.10
213	31.75	42.16	31.88	Sludge Recycle	PVC	80	-	60	-	35.85	14.65	5.10
214	90.00	101.6	90.12	Biogas Transport Line	DSS	STD	36	1425	1.3	122.94	116.21	5.06
215	90.00	101.6	90.12	Biogas Transport Line	DSS	STD	36	1425	1.1	122.94	-	-
216	90.00	101.6	90.12	Biogas Transport Line	DSS	STD	35	1425	1.2	122.94	116.21	5.06
301	25.40	33.40	26.14	Dosing water	CPVC&CGI	40	27	60	1.2	31.03	8.33375	4.31
302	25.40	33.40	26.14	Dosing water	CPVC&CGI	40	27	60	1.2	31.03	8.33375	4.31
303	25.40	33.40	26.14	Dosing water	CPVC&CGI	40	27	60	1.2	31.03	8.33375	4.31
304	25.40	33.40	26.14	Dosing water	CPVC&CGI	40	25	60	1.4	31.03	8.33375	4.31
305	25.40	33.40	26.14	Dosing water	CPVC&CGI	40	25	60	1.8	31.03	8.33375	4.31
306	25.40	33.40	26.14	Dosing water	CPVC&CGI	40	25	60	1.8	31.03	8.33375	4.31

Material codes:

PVC – Poly vinyl chloride
CPCV- Chlorinated Polyvinyl chloride
DSS – Duplex Stainless Steel
SS – Stainless steel 316
CGI- cellulose glass insulation

APPENDIX D – VALVE SCHEDULE

Table D: Valve Schedule

Valve ID	Description	Type	Material	Position
HV-101	Feed Sump manual drain	Gate	CI	Closed
HV-102	Pump suction side isolation valve	Knife gate	SS316	Open
HV-103	Pump drain valve	Gate	CI	Closed
HV-104	Pump discharge valve	Knife gate	SS316	Open
HV-105	Backup pump suction side isolation valve	Knife gate	SS316	Closed
HV-106	Backup pump drain valve	Gate	CI	Closed
HV-107	Backup pump discharge valve	Knife gate	SS316	Closed
HV-108	Buffer tank drain valve	Gate	SS316	Closed
HV-109	Pump suction side isolation valve	Knife gate	SS316	Open
HV-110	Pump drain valve	Gate	CI	Closed
HV-111	Pump discharge valve	Knife gate	SS316	Open
HV-112	Backup pump suction side isolation valve	Knife gate	SS316	Closed
HV-113	Pump drain valve	Gate	CI	Closed
HV-114	Backup pump discharge valve	Knife gate	SS316	Closed
HV-115	Control valve isolation valve	Knife gate	SS316	Open
HV-116	Drain valve	Gate	CI	Closed
HV-117	Control valve isolation valve	Knife gate	SS316	Open
HV-118	Manual bypass valve	Gate	CI	Closed
HV-119	Sampling port	Gate	CI	Closed
HV-120	Heat Exchanger drain valve	Ball Valve	CI	Closed
HV-121	Control valve drain	Gate	CI	Closed
HV-122	TCV-101 isolation valve	Butterfly	CI	Open
HV-123	TCV-101 isolation valve	Butterfly	CI	Open
HV-124	Control valve TCV-101 bypass	Gate	CI	Closed
HV-125	Heat exchanger drain valve	Ball valve	CI	Closed
HV-126	Steam trap drain valve	Ball valve	CI	Closed
HV-127	TK-101 drain valve	Gate valve	CI	Closed
CV-101	Non-return valve for the pump	Swing Check valve	SS316	-
CV-102	Non-return valve for the backup pump	Swing Check valve	SS316	-
CV-103	Non-return valve for the pump	Swing Check valve	SS316	-
CV-104	Non-return valve for the backup pump	Swing Check valve	SS316	-

TCV-101	Effluent heating flow control valve	Pinch valve	CS	Fail closed
TCV-102	Steam flow control valve	Ball valve	SS316	Fail open
LCV-101	Influent level control valve	Pinch valve	CS (Neoprene sleeve)	Fail open
LCV-102	Calamity tank control valve	Pinch valve	CS (Neoprene sleeve)	Fail closed
HV-201	Control valve isolation	Knife gate	SS316	Closed
HV-202	Control valve isolation	Knife gate	SS316	Closed
HV-203	Manual control valve bypass	Gate	SS316	Closed
HV-204	Biogas valve	Gate	SS316	Open
HV-205	Pump suction side isolation valve	Knife gate	SS316	Open
HV-206	Pump drain valve	Gate	CI	Closed
HV-207	Pump drain valve	Knife gate	SS316	Open
HV-208	Backup pump discharge valve	Knife gate	SS316	Open
HV-209	Pump drain valve	Gate	CI	Closed
HV-210	Pump suction side isolation valve	Knife gate	SS316	Open
HV-211	Backup pump discharge valve	Knife gate	SS316	Closed
HV-212	Pump drain valve	Gate	CI	Closed
HV-213	Backup pump suction side isolation valve	Knife gate	SS316	Closed
HV-214	Sludge sampling valve	Knife gate	SS316	Closed
HV-215	Reactor effluent sampling port	Knife gate	SS316	Closed
HV-216	Backup pump suction side isolation valve	Knife gate	SS316	Closed
HV-217	Pump drain valve	Gate	CI	Closed
HV-218	Backup pump discharge valve	Knife gate	SS316	Closed
HV-219	Pump suction side isolation valve	Knife gate	SS316	Open
HV-220	Pump drain valve	Gate	CI	Closed
HV-221	Pump discharge valve	Knife gate	SS316	Open
HV-222	Clarifier drain valve	Gate	CI	Closed
HV-223	Sampling port	Ball	CI	Closed
HV-224	Degasser drain valve	Gate	CI	Closed
HV-225	Clarifier sump drain	Gate	CI	Closed
CV-201	Non-return valve for the pump	Swing Check valve	SS316	-
CV-202	Backup non-return valve for the pump	Swing Check valve	SS316	-
CV-203	Backup non-return valve for the pump	Swing Check valve	SS316	-
CV-204	Non-return valve for the pump	Swing Check valve	SS316	-
CV-205	Non-return valve for the pump	Swing Check valve	SS316	-
PCV-201	Calamity tank drain control valve	Pinch	CI (Neoprene sleeve)	-

HV-301	Backup pump suction side isolation valve	Knife gate	SS316	Closed
HV-302	Pump drain valve	Gate	CI	Closed
HV-303	Backup pump suction side isolation valve	Knife gate	SS316	Closed
HV-304	Pump suction side isolation valve	Knife gate	SS316	Open
HV-305	Pump discharge valve	Knife gate	SS316	Open
HV-306	Pump drain valve	Gate	CI	Closed
HV-307	V-302 tank drain valve	Gate	CI	Closed
HV-308	Kickback line control valve isolation	Knife gate	SS316	Open
HV-309	Kickback line control valve isolation	Knife gate	SS316	Open
HV-310	Kickback line manual bypass valve	Gate	SS316	Closed
HV-311	Pump suction side isolation valve	Knife gate	SS316	Open
HV-312	Pump drain valve	Gate	CI	Closed
HV-313	Pump discharge valve	Knife gate	SS316	Open
HV-314	Backup pump suction side isolation valve	Knife gate	SS316	Closed
HV-315	Pump drain valve	Gate	CI	Closed
HV-316	Backup pump discharge valve	Knife gate	SS316	Closed
CV-301	Non-return valve for the pump	Swing Check valve	SS316	-
CV-302	Non-return valve for the pump	Swing Check valve	SS316	-
CV-303	Non-return valve for the kickback line	Swing Check valve	SS316	-
CV-304	Non-return valve for the pump	Swing Check valve	SS316	-
CV-305	Non-return valve for the pump	Swing Check valve	SS316	-
ACV-301	Lime dosing control valve	Pinch	CI (Neoprene sleeve)	Fail open
FCV-301	Water control mixing line	Pinch	CI (Neoprene sleeve)	Fail closed

Material codes:

SS316 – Stainless steel 316

CI – Cast Iron

CS – Carbon steel

APPENDIX E – INSTRUMENT SCHEDULE

Table E: Instrument Schedule

Instrument ID	Description	Display Point	Type	Principle	Unit	Range		Alarm levels			
						Low	High	LL	L	H	HH
LIT-101	Reads and displays the level from the sensor LE-101	Field	Indicator and Transmitter	Float with switch	m water	0	8	0.7	1	-	7.5
LE-102	Reads and transmits the level reading to the transmitter then to the controller	Field	Sensor	Float and switch	m water	0	3.5	0.2	-	-	3
TE-101	Reads the temperature of the influent wastewater.	Field	Sensor	Thermocouple	°C	0	30	-	-	-	-
FE-101	Reads the exit flowrate of the buffer tank TK-102	Field	Sensor	Orifice plate	m^3/h	0	70				
TE-102	Reads the temperature of the effluent stream heading into the heating reactor E-101	Field	Sensor	Thermocouple	°C	0	40	-	-	-	-
FI-101	Steam Flow Indicator	Field	Sensor Indicator	Orifice Plate	m^3/h	0	34	-	-	-	-
TIC-103	Temperature measurement of the digester	Field	Sensor	Thermistor	°C	20	50	-	34	39	-
TIC-104	Temperature of the influent just before the digester	Field	Sensor	Thermistor	°C	20	50	-	-	-	-
AE-201	Methane detection sensor	Field	Sensor	Infrared Methane Sensor	%	0	100	-	-	-	-
AE-301	pH Detection	Field	Sensor	pH probe	pH	6	8	-	6.8	7.2	-
LE-201	Reactor level	Field	Sensor	conductivity switch	m water	0	17.4	-	-	15	16
PE-201	Pressure measurement sensor	Field	Sensor	Piezo-resistive pressure sensors	kPa	0	500	-	-	190	400
PI-201	Pressure measurement indicator	Field	Sensor and Indicator	Pressure Gauge	kPa	0	400	-	-	-	-
FIT-201	Flow indicator and transmitter	Field	Indicator and transmitter	Ultrasonic flowrate	m^3/h	0	20	-	-	-	-
TIT-201	Temperature indicator and transmitter	Field	Indicator and transmitter	Thermistor	°C	10	40	25	-	-	40
LE-202	Clarifier level sensor	Field	Temperature sensor	Float and switch	m water	0	6	2	-	-	5.8

FE-301	Flow sensor	Field	Flow sensor	Orifice plate	m^3/h	0	250	-	-	-	-
LT-301	Level Controller indicator	Field	Indicator transmitter	Float and switch	m water	0	4	1	-	-	3.7

APPENDIX F – DATA SHEET AND CALCULATIONS

F.1 Reactor Feed Pump – P-102 A/B

Equipment Name	Feed Pump P-102 A/B	
Pump Type	Centrifugal	
Mass Flowrate	16.81	kg/s
Re	2.70E+05	
Kvalue	12.80	
Velocity Head	0.79	m
Pressure Loss	184.52	kPa
Efficiency	65%	
Power Required	2.17	kW
$NPSH_{avail}$	91.56	m
Head loss	9	m
Impeller Type	Semi-open	
Impeller Vane	Backward	
Impeller Material	nickel-aluminium-bronze	

The method outlined in (Sinnott, 2005).

The first step is to obtain the superficial velocity

The required volumetric flowrate out of the pump is $1410\frac{m^3}{d} = 0.016\frac{m^3}{s}$

Using the density of the slurry the mass flowrate can be calculated $\dot{m} = 16.8\frac{kg}{s}$

The equivalent mass flowrate (assuming a constant slurry density of $1030\frac{kg}{m^3}$.

The pipe inner diameter was calculated and displayed in Table C. The inner diameter $d_i = 72.75\ mm$

This allows for the cross-sectional area to be calculated:

$$A_c = \pi\left(\frac{D}{2}\right)^2$$
$$A_c = 0.004\ m^2$$

This allows for the superficial velocity to be calculated.

$$u = \frac{\dot{Q}}{A_c}$$
$$u = \frac{0.016}{0.004}$$
$$u = 2.92\frac{m}{s}$$

The Reynolds number is then calculated.

The density remains as $\rho_{slurry} = 1030\frac{kg}{m^3}$

The viscosity was assumed to be slightly higher than that for pure water owing to the additional solids therefore.

$$\mu = 0.00109\ Pa.s$$

Together the Reynolds number can be obtained

$$Re = \frac{\rho_{slurry} u\ d_i}{\mu}$$
$$Re = \frac{1030 * 2.92 * 0.07}{0.00109}$$
$$Re = 269989$$

This shows that the regime is clearly turbulent which is associated with higher shear values.

The relative roughness can now be obtained. The roughness for PVC was obtained in (Sinnott, 2005) to be $e_{abs} = 0.00015$ and the relative roughness (per pipe diameter) is $e_{rel} = 2.062E - 6$.

The friction factor in Figure 5.7 in (Sinnott, 2005) and was found to be 0.00175.

The fitting and valve velocity heads were totalled. The values were obtained from (Sinnott, 2005) and are shown below. Figure F1 was used to estimate the number of bends required and the P&ID was used to determine the number of valves. The distances were obtained from (Layout, 2015) which detailed the minimum distances required between certain process units.

Fittings and Valves			
	k val	number	TOTAL
45 deg LRE	0.2	1	0.2
90 deg	0.6	5	3
Sharp Exp	1	3	3
sharp red	0.5	5	2.5
Check	1	1	1
Gate	0.15	4	0.6
Pinch	1.3	1	2.5
			12.8

From here the pressure can be obtained.

The velocity head is calculated as follows:

$$u_h = \frac{u}{2 * 9.81}$$
$$u_h = \frac{3.93}{2 * 9.81}$$
$$u_h = 0.79 \frac{m}{s}$$

The pressure headloss is calculated as follows:

$$\Delta P_h = u_h * \rho_{slurry} * K * 9.81$$

$$\Delta P_h = 0.79 * 1030 * 12.8 * 9.81$$
$$\Delta P_h = 101659\ Pa$$

The total length of the piping that the fluid is being pumped over

Was calculated through Figure F1 (plant layout) and Figure F2 (profile view)

The total length is equal to the straight line distance between the pump and the reactor (Figure F1) as well as the vertical pipe distances Figure F2.

$$L_p = L_{straight\ Line} + L_{Vertical}$$
$$L_p = (3.1 + 1.5 + 25) + (14.6)$$
$$L_p = 44.2\ m$$

The pressure drop due to frictional losses in the pipeline is:

$$\Delta P_f = \frac{8f\left(\frac{L}{d_i}\right)\rho u^2}{2}$$
$$\Delta P_f = 8 * 0.00175 * \left(\frac{44.2}{0.07275}\right) * 1030 * \frac{3.93^2}{2}$$
$$\Delta P_f = 67482\ Pa$$

The heat exchanger losses (calculated below) (it was assumed that the pressure drop for both heat exchangers are equal.

$$\Delta P_{HX} = 2 * 7690.9\ Pa$$
$$\Delta P_{HX} = 15381.9\ Pa$$

$$\Delta P_{total} = \Delta P_h + \Delta P_f + \Delta P_{HX}$$
$$\Delta P_{total} = 101659 + 67482 + 15381.9$$
$$\Delta P_{total} = 184523.6195\ Pa$$

From here the specific energy can be calculated using the following equation (Sinnott, 2005):

$$w = \frac{\Delta P}{\rho} + g\Delta z - \frac{\Delta P_f}{\rho}$$

The difference in system pressures are calculated:

$$\Delta P = P_1 - P_2$$

The buffer tank (TK-102) pressure P_1 is calculated using a liquid level if 6 meters:

$$P_1 = \rho g h$$
$$P_1 = 1030 * 9.81 * 6$$
$$P_1 = 161968.5\ Pa$$

The reactor (R-201) is fed just below the liquid level to prevent having to overcome the liquid head of the reactor, but still ensuring that no biogas flows back into the line. This value was calculated in the previous section to be:

$$P_2 = 101473.7\ Pa$$

Therefore:

$$\Delta P = P_1 - P_2 = 161968.5 - 101473.7$$
$$\Delta P = 60494.8\ Pa$$

The distance from the datum (Figure F2) is:

$$\Delta z = (0 - 8)$$
$$\Delta z = -8$$

The specific energy required can be calculated:

$$w = \frac{\Delta P}{\rho} + g\Delta z - \frac{\Delta P_f}{\rho}$$
$$w = \frac{60494.8\ Pa}{1030} + 9.81(-8) - \frac{67482}{1030}$$
$$w = -198.9\frac{J}{kg}$$

The work required by the pump can be calculated:

$$W_{ideal} = w * \dot{m}$$
$$W_{ideal} = -198.9(16.8)$$
$$W_{ideal} = -3343.6\frac{J}{s}$$

For an efficiency of 65%

$$W_{actual} = \frac{W_{ideal}}{65\%}$$
$$W_{actual} = \frac{3343.6\frac{J}{s}}{65\%}$$
$$W_{actual} = 2.2\ kW$$

The $NPSH_{avail}$ can be calculated (Sinnott, 2005).

$$NPSH_{avail} = \frac{P}{\rho} + H - \frac{P_f}{\rho} - \frac{P_v}{\rho}$$

The pressure (P) above the liquid in the feed vessel is at atmospheric pressure (101325 Pa) (Sinnott, 2005).

P_f is the pressure loss in the suction piping.

The L in this case is the total length of piping before the pump (since that correlates with the definition of $NPSH_{avail}$) (Sinnott, 2005).

$$P_f = \frac{8f\left(\frac{L}{d_i}\right)\rho u^2}{2}$$

$$P_f = \frac{8 * 0.00175 * \left(\frac{6}{0.07275}\right) * 1030 * 3.9^2}{2}$$
$$P_f = 9171 \; Pa$$

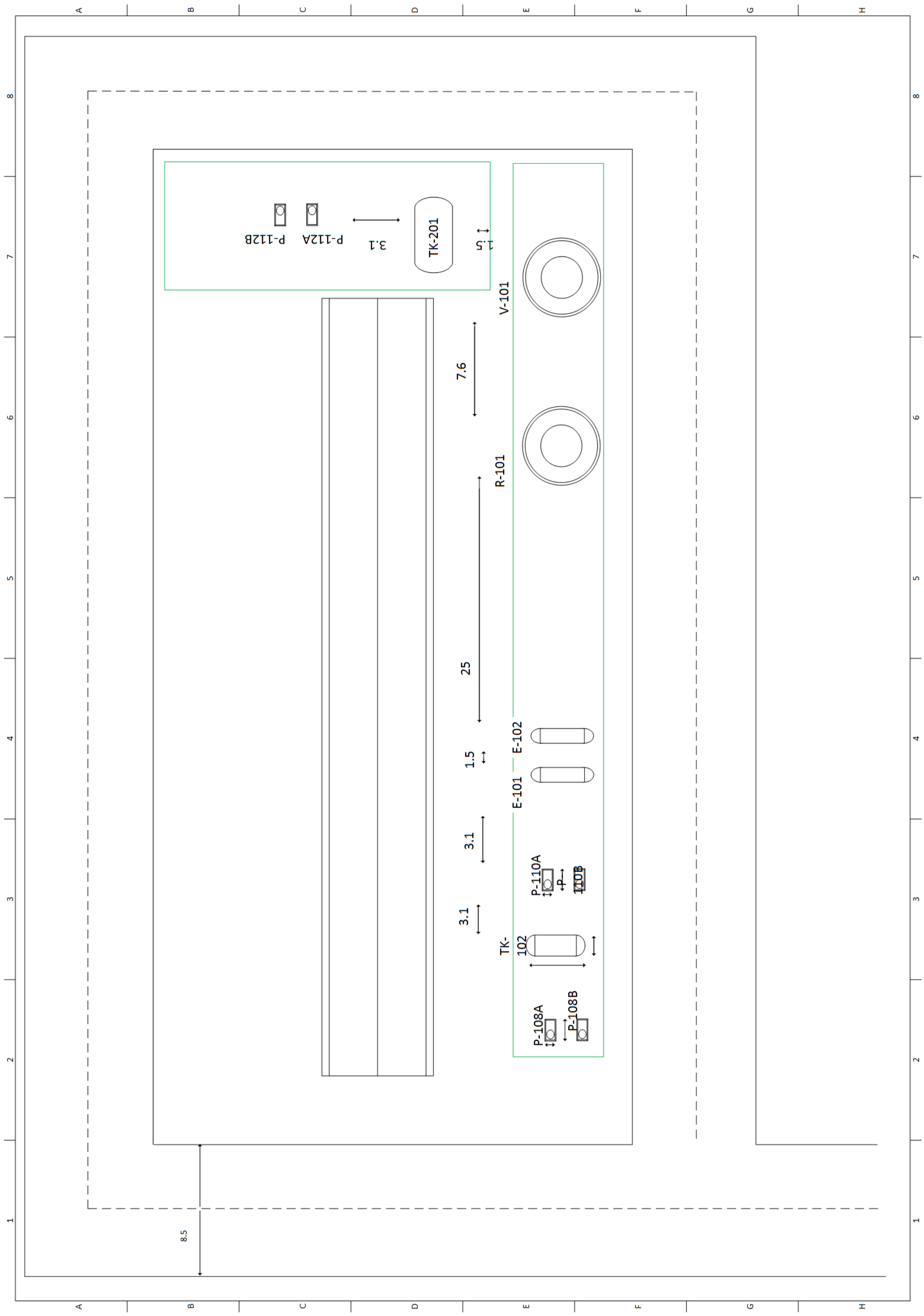
P_v is simply the vapour pressure of water (4000 Pa)

No the $NPSH_{avail}$ can be calculated

$$NPSH_{avail} = \frac{101325}{1030} + 6 - \frac{9171}{1030} - \frac{4000}{1030}$$
$$NPSH_{avail} = 92 \; m$$

Therefore a pump is needed with a $NPSH_{req}$ less than 92m.

Figure F1


TK-201
P-112A
P-112B
V-101
R-101
E-101
E-102
P-110A
TK-102
P-108A
P-108B
7.6
25
1.5
3.1
8.5

F.1 Feed steam heat exchanger – E-102

Type	Shell and Tube	
Material of construction	Stainless Steel 316	
Cold Component	Industrial Wastewater	
Hot Component	Steam	
Maximum Pressure	4	bar
Heat Transfer Area	33.4	m2
Area per Plate	1.45	m2
Number of Plates	23.00	
Plate Spacing	5	mm
Plate Thickness	0.8	mm
Wastewater Flowrate	60525	kg/h
Steam Flowrate	2192.38	kg/h
Heating Requirement	1378.63	kW

Assumptions

- Effluent heat exchanger is non-operational
- Constants for WW based on water as its majority
- Steady-State
- Counter-Current setup
- Constant Density
- Average heat capacities

The procedure is detailed in (Sinnott, 2005).
The duty was first calculated.
From the previous section the mass flowrate of the wastewater is: $\dot{m} = 60525\frac{kg}{h} = 16.8\frac{kg}{s}$
The volumetric flowrate of the wastewater is: $\dot{Q} = 17\frac{m^3}{h} = 0.016\frac{m^3}{s}$

The heat capacity of the inlet wastewater is 4.16 kJ/kg.K and outlet 4.07 kJ/kg.K.
This was averaged to give $C_P = 4.1\frac{kJ}{kg\ K}$

The wastewater enters at t_1=17^{O}C
(Assuming that the effluent heat exchanger is non-functional such as during start-up or when the effluent temperature is under the influent wastewater temperature)
Exit steam temperature is t_2=37^{o}C
The steam enters at 4 bar and T_1=140^{o}C
It exits as liquid at T_2=139^{o}C

The heating requirement of the wastewater is:

$$Q = \dot{m}C_p\Delta T$$
$$Q = 60525 * 4.1 * (37 - 17)$$
$$Q_{ww} = 4963050\frac{kJ}{h} = 1378.63\frac{kJ}{s}$$

The steam flowrate can now be calculated using the energy balance for a phase change

$$Q_{ww} = \dot{m}h + \dot{m}Cp\Delta T$$
$$\dot{m} = \frac{Q_{ww}}{h + Cp\Delta T}$$

$$\dot{m} = \frac{-4963050}{2260 + 3.77(139 - 140)}$$
$$\dot{m_w} = 2192\frac{kg}{h} = 0.61\frac{kg}{s}$$

With h being the heat of vaporization in kJ/kg.K

The log mean temperature is then calculated:

$$\Delta T_{lm} = \frac{(T_1 - t_2) - (T_2 - t_1)}{\ln\left(\frac{T_1 - t_2}{T_2 - t_1}\right)}$$
$$\Delta T_{lm} = \frac{(140 - 37) - (139 - 17)}{\ln\left(\frac{140 - 37}{139 - 17}\right)}$$
$$\Delta T_{lm} = 112\ degrees\ celcius$$

NTU was calculated:

$$NTU = \frac{t_1 - t_2}{\Delta T_{LM}}$$
$$NTU = \frac{17 - 37}{112}$$
$$NTU = 0.17$$

The log mean correction factor F_t was read off of Figure 12.62 in (Sinnott, 2005).

$$F_t = 0.95$$

The corrected LMT is

$$T_{cLMT} = 107\ degrees\ celcius$$

The overall heat transfer coefficient is guessed (this is the last iteration)

$$U_o = 387.6\frac{W}{m^2C}$$

The heat transfer area is as follows:

$$A = \frac{Q}{U_o \Delta \mathrm{T_{cLMTD}}}$$
$$A = \frac{1378.6\frac{kJ}{s} * 1000\frac{J}{kJ}}{387.6\ \frac{W}{m^2C} * 107\ C}$$
$$A = 33.4\ m^2$$

The area per a plate was estimated to be 1.45. the width to length ratio was estimated to be 2.

$$L = \sqrt{\frac{1.45}{2}}$$
$$L = 0.85$$
$$w = 2 * 0.85$$
$$w = 1.7\ m$$

The number of plates was calculated:

$$Nr_{plates} = \frac{A}{\frac{A}{plate}}$$
$$Nr_{plates} = \frac{33.4}{1.45}$$
$$Nr_{plates} = 23$$

The number of channels per pass: 11

The plate spacing was selected as 5mm and the plate thickness is 0.8mm. This thin plate thickness is possible due to the low pressures.

The channel area is:

$$A_{channel} = w_{plate} * t_{platespace}$$
$$A_{channel} = 1.7 * 5/1000$$
$$A_{channel} = 0.0085\, m^2$$

The hydraulic mean diameter:

$$d_h = \frac{t_{platespace}}{1000} * 2$$
$$d_h = 0.01\, m$$

Now the overall heat transfer coefficient is calculated and verified.

<u>For waste water:</u>

the channel velocity first needs to be calculated

$$u_p = \frac{\dot{m}_{ww}}{\rho} * \frac{1}{A_{channel}} * \frac{1}{Nr_{plates}}$$
$$u_p = \frac{16.81}{1030} * \frac{1}{0.0085} * \frac{1}{23}$$
$$u_p = 0.17 \frac{m}{s}$$

Followed by the Reynolds number

$$Re = \frac{\rho_{slurry} u_p\, d_h}{\mu}$$
$$Re = \frac{1030 * 0.17 * 0.01}{0.000798}$$
$$Re = 2249$$

Then the Prandtl number

$$\mathrm{Pr} = Cp * \frac{\mu}{kf}$$
$$\mathrm{Pr} = 4.1 * \frac{0.000798}{0.59}$$
$$Pr = 5.6$$

Then Nusselt number

$$Nu = 0.26 * Re^{0.65} * Pr^{0.4}$$
$$Nu = 0.26\, (2249)^{0.65} * 5.6^{0.4}$$
$$Nu = 78$$

$$h_p = Nu * \frac{k_f}{d_h}$$
$$h_p = 78 * \frac{0.59}{0.01}$$
$$h_{p,ww} = 4601 \frac{W}{m^2 C}$$

<u>The same was done for the steam:</u>

$$u_p = \frac{\dot{m}_{ww}}{\rho} * \frac{1}{A_{channel}} * \frac{1}{Nr_{plates}}$$

$$u_p = \frac{0.61}{1030} * \frac{1}{0.0085} * \frac{1}{23}$$
$$u_p = 0.006\frac{m}{s}$$

Followed by the Reynolds number

$$Re = \frac{\rho_{slurry} u_p \, d_h}{\mu}$$
$$Re = \frac{900 * 0.006 * 0.01}{0.000798}$$
$$Re = 230$$

Then the Prandtl number

$$\mathrm{Pr} = Cp * \frac{\mu}{kf}$$
$$\mathrm{Pr} = 3.9 * \frac{0.000282}{0.3}$$
$$Pr = 3.7$$

Then Nusselt number

$$Nu = 0.26 * Re^{0.65} * Pr^{0.4}$$
$$Nu = 0.26\,(230)^{0.65} * 3.7^{0.4}$$
$$Nu = 15$$

$$h_p = Nu * \frac{k_f}{d_h}$$
$$h_p = 15 * \frac{0.3}{0.01}$$
$$h_{p,w} = 452\frac{W}{m^2C}$$

The fouling factors were obtained for the wastewater treatment water and the process water.

$$h_{fouling\ ww} = 5000\frac{W}{m^2C}$$
$$h_{fouling\ w} = 15000\ \frac{W}{m^2C}$$
$$h_{p,ww} = 4601\frac{W}{m^2C}$$
$$h_{p,w} = 452\frac{W}{m^2C}$$

The overall heat transfer coefficient was calculated

$$\frac{1}{U_o} = \frac{1}{h_{fouling\ ww}} + \frac{1}{h_{fouling\ w}} + \frac{1}{h_{p,ww}} + \frac{1}{h_{p,w}} + \frac{t_{thickness}}{1000 * k_w}$$
$$\frac{1}{U_o} = \frac{1}{5000} + \frac{1}{15000} + \frac{1}{4601} + \frac{1}{452} + \frac{0.8}{1000 * 15}$$

$$U_{o,calc} = 363.9\frac{W}{m^2C}$$
$$U_{o,est} = 387.6\frac{W}{m^2C}$$

The estimate is within 10% of each other. If not then the U is estimated again then the process is repeated.

Now the pressure drop can be calculated.

The pressure due to the wastewater is higher than the pressure drop for the steam (calculated as follows, the steam calculation is left out for brevity)

$$j_F = 0.6 * Re^{-0.3}$$
$$j_F = 0.6 * 2249^{-0.3}$$
$$j_F = 0.06$$

The path length was calculated which is estimated to be the same as the length of the plate.

$$u_p = 0.17 \frac{m}{s}$$

$$\Delta P_p = 8 * \ 0.06 * \left(\frac{0.85}{0.17}\right) * \frac{1030 * 0.17^2}{2}$$
$$\Delta P_p = 631 \ Pa$$

The port size was estimated to be 800mm

The area of the port is 0.005 m^2

Velocity through the port is:

$$u_{port} = \frac{\dot{Q}}{A_{port}}$$
$$u_{port} = \frac{0.016}{0.005}$$
$$u_{port} = 3.2 \frac{m}{s}$$

And-a-finally the pressure drop

$$\Delta P_{pt} = 1.3 \frac{(\rho u_{pt}^2)}{2} N_p$$
$$\Delta P_{pt} = 1.3 \frac{1030 * 3.2^2}{2} (1)$$
$$\Delta P_{pt} = 7060 \ Pa$$

$$P_{total} = \ \Delta P_p + \Delta P_{pt}$$
$$P_{total} = 631 + 7060$$

$$P_{total} = \ \ 7690.9 \ Pa$$

F.1 Clarifier – V-202

Type	Circular	
Feed Method	Centre	
Material of Construction	Concrete C25/30	
Total Height	5.90	m
Freeboard	0.50	m
Scum baffle	None	
Launder Thickness	0.03	m
Sidewall Thickness (above ground)	0.09	m
Sidewall Thickness (Below Ground)	0.08	m

Rake Motor	Spur Gear
Motor Casing	Cast Iron
Gear material	Stainless Steel 304
Rake Construction	Stainless Steel 316

The method is followed as per that demonstrated in (Qasim and Zhu, 2017).

No weir as no scum will form.

A circular clarifier with a centre feed was selected
2 clarifiers were estimated for the first run
The maximum loading was estimated to size the clarifier. Evaporation and rain were not considered for the first estimate.
The flowrate is obtained from the mass balance.

$$Q_{in} = 2079 \frac{m^3}{d}$$

$$C_{in} = 13778 \frac{mg}{L} = 13.78 \frac{kg}{m^3}$$

$$C_u = 57500 \frac{mg}{L}$$

The average concentration between the underflow and inflow Ctz

$$C_{tz} = 35.64 \frac{kg}{m^3} = 35639 \frac{mg}{L}$$

The overflow

$$Q_o = 1417.7 \frac{m^3}{d}$$

$$Q_u = 767.7 \frac{m^3}{d}$$

The SLR and SOR are estimated:

$$SLR = 4 \frac{kg}{m^2\ h}$$

$$SOR = 16 \frac{m^3}{m^2 d}$$

Calculate area using both the SOR and SLR. Use the biggest one.

$$A_{SOR} = \frac{Q_o}{SOR}$$

$$A_{SOR} = \frac{1417.7}{16}$$
$$A_{SOR} = 88.6\, m^2$$

$$A_{SLR} = \frac{Q_o}{SLR}$$
$$A_{SLR} = \frac{1417.7}{4}$$
$$A_{SLR} = 259\, m^2$$

Calculate the diameter using the SLR area

$$D_{calc} = 18.2\, m$$

Round off

$$D_{calc} = 18\, m$$

The dimensions can be calculated.

The reactor volume per clarifier: 2299 m^3
The mass of TSS in the reactor:

$$m_{TSS} = 2299 \frac{V_{reactor}}{clarifier} * C_{in}$$
$$m_{TSS} = 31669\, kg$$

Assuming no biological activity occurs in the clarifier.
Therefore the thickening zone and sludge storage zone can be combined.

$$H_{tz} + H_{sz} = \frac{m_{TSS}}{A * Ctz}$$
$$H_{tz} + H_{sz} = \frac{31669}{259 * 35.64}$$
$$H_{tz} + H_{sz} = 3.43\, m$$

The clear water and settling zone depth was select as:

$$H_{csz} = 2.5\, m$$

The total height of the clarifier is: 5.9m

The launder (made of concrete) thickness was selected as 0.3m (Qasim and Zhu, 2017).
The circumference of the launder is 54.66
The weir loading rate is $\frac{Q_o}{C_{launder}} = \frac{1417}{54.66} = 25.9 \frac{m^3}{m.d}$

F.1 Sludge recycle pump – P-203 A/B

Equipment Name	Sludge Recycle Pump P-203A/B	
Pump Type	Rotary Lobe	
Mass Flowrate	4.65	kg/s
Re	1.45E+05	
Kvalue	9.20	
Velocity Head	0.85	m
Pressure Loss	164.64	kPa
Efficiency	65%	
Power Required	0.66	kW
$NPSH_{avail}$	81.75	m
Head loss	4	m
Lobes	Acrylonitrile Butadiene Rubber	
Number of Lobes	4 lobes	
Casing	Carbon Steel	
Wear Plates	AR500 Steel	
Strain Bolts	Carbon Steel, Geomet Coating	
Pump Cover	A48 Gray Iron	
Timing Gears	1045 Steel, AGMA Class 9	
Shafts	AISI A4140 Steel	

This is calculated in exactly the same way as the centrifugal pump, except the NPSH calculation will differ.

The method outlined in (Sinnott, 2005).

The first step is to obtain the superficial velocity

The required volumetric flowrate out of the pump is $399 = 0.005\frac{m^3}{s}$

Using the density of the slurry the mass flowrate can be calculated $\dot{m} = 4.6\frac{kg}{s}$

The equivalent mass flowrate (assuming a constant slurry density of $1030\frac{kg}{m^3}$.

The pipe inner diameter was calculated and displayed in Table C. The inner diameter $d_i = 37.5\ mm$

This allows for the cross-sectional area to be calculated:

$$A_c = \pi\left(\frac{D}{2}\right)^2$$

$$A_c = 0.001\ m^2$$

This allows for the superficial velocity to be calculated.

$$u = \frac{\dot{Q}}{A_c}$$

$$u = 2.92\frac{m}{s}$$

The Reynolds number is then calculated.

The density remains as $\rho_{slurry} = 1030 \frac{kg}{m^3}$

The viscosity was assumed to be slightly higher than that for pure water owing to the additional solids therefore.

$$\mu = 0.00109\ Pa.s$$

Together the Reynolds number can be obtained

$$Re = \frac{\rho_{slurry} u\ d_i}{\mu}$$
$$Re = \frac{1030 * 4.087 * 37.5/1000}{0.00109}$$
$$Re = 144830.4808$$

This shows that the regime is clearly turbulent which is associated with higher shear values.

The relative roughness can now be obtained. The roughness for PVC was obtained in (Sinnott, 2005) to be $e_{abs} = 0.00015$ and the relative roughness (per pipe diameter) is $e_{rel} = 4.00107E - 06$.

The friction factor in Figure 5.7 in (Sinnott, 2005) and was found to be 0.00175.

The fitting and valve velocity heads were totalled. The values were obtained from (Sinnott, 2005) and are shown below. Figure F1 was used to estimate the number of bends required and the P&ID was used to determine the number of valves. The distances were obtained from (Layout, 2015) which detailed the minimum distances required between certain process units.

Fittings and Valves			
	k val	number	TOTAL
45 deg LRE	0.2	0	0
90 deg	0.6	4	2.4
Sharp Exp	1	2	2
sharp red	0.5	2	1
Check	1	1	1
gate	0.15	2	0.3
tee entry	1.8	2	2.5
			9.2

From here the pressure can be obtained.

The velocity head is calculated as follows:

$$u_h = \frac{u}{2 * 9.81}$$
$$u_h = 0.85 \frac{m}{s}$$

The pressure headloss is calculated as follows:

$$\Delta P_h = u_h * \rho_{slurry} * K * 9.81$$
$$\Delta P_h = \ 0.85 * 1030 * 9.2 * 9.81$$
$$\Delta P_h = 79165.5\ Pa$$

The total length of the piping that the fluid is being pumped over

Was calculated through Figure F1 (plant layout).

The total length is equal to the straight line distance between the pump and the reactor (Figure F1) as well as the vertical pipe distances.

$$L_p = L_{straight\ Line} + L_{Vertical}$$
$$L_p = 26.6$$

The pressure drop due to frictional losses in the pipeline is:

$$\Delta P_f = \frac{8f\left(\frac{L}{d_i}\right)\rho u^2}{2}$$
$$\Delta P_f = 8 * 0.00175 * \left(\frac{44.2}{0.07275}\right) * 1030 * \frac{3.93^2}{2}$$
$$\Delta P_f = 85475.7\ Pa$$

The heat exchanger losses (calculated below) (it was assumed that the pressure drop for both heat exchangers are equal.

$$\Delta P_{HX} = \ 2 * 7690.9\ Pa$$
$$\Delta P_{HX} = \ 15381.9\ Pa$$

$$\Delta P_{total} = \Delta P_h + \Delta P_f + \Delta P_{HX}$$
$$\Delta P_{total} = 101659 + 67482 + 15381.9$$
$$\Delta P_{total} = 1164641.2\ Pa$$

From here the specific energy can be calculated using the following equation (Sinnott, 2005):

$$w = \frac{\Delta P}{\rho} + g\Delta z - \frac{\Delta P_f}{\rho}$$

The difference in system pressures are calculated:

$$\Delta P = \ P_1 - P_2$$

$$P_1 = \rho g h$$
$$P_1 = \ \ 103346.4486 Pa$$

$$P_2 = 101473.7\ Pa$$

Therefore:

$$\Delta P = P_1 - P_2$$

$$\Delta P = 1872.8\ Pa$$

The distance from the datum is:

$$\Delta z = (0 - 8)$$
$$\Delta z = -8$$

The specific energy required can be calculated:

$$w = \frac{\Delta P}{\rho} + g\Delta z - \frac{\Delta P_f}{\rho}$$
$$w = \frac{1872.8\ Pa}{1030} + 9.81(-8) - \frac{85475.7}{1030}$$
$$w = -236.5 \frac{J}{kg}$$

The work required by the pump can be calculated:

$$W_{ideal} = w * \dot{m}$$
$$W_{ideal} = 236.5(4.6)$$
$$W_{ideal} = -1099.138623 \frac{J}{s}$$

For an efficiency of 65%

$$W_{actual} = \frac{W_{ideal}}{65\%}$$
$$W_{actual} = \frac{-1099.138623 \frac{J}{s}}{65\%}$$
$$W_{actual} = 0.7kW$$

The $NPSH_{avail}$ can be calculated (Sinnott, 2005).

$$NPSH_{avail} = \frac{P}{\rho} + H - \frac{P_f}{\rho} - \frac{P_v}{\rho}$$

The pressure (P) above the liquid in the feed vessel is at atmospheric pressure (101325 Pa) (Sinnott, 2005).

P_f is the pressure loss in the suction piping.

The L in this case is the total length of piping before the pump (since that correlates with the definition of $NPSH_{avail}$) (Sinnott, 2005).

$$P_f = \frac{8f\left(\frac{L}{d_i}\right)\rho u^2}{2}$$
$$P_f = \frac{8 * 0.00175 * \left(\frac{6}{0.03749}\right) * 1030 * 4.09^2}{2}$$
$$P_f = 19280.22998\ Pa$$

P_v is simply the vapour pressure of water (4000 Pa)

No the $NPSH_{avail}$ can be calculated

$$NPSH_{avail} = \frac{101325}{1030} + 6 - \frac{19280.22998}{1030} - \frac{4000}{1030}$$
$$NPSH_{avail} = 92\ m$$

Therefore a pump is needed with a $NPSH_{req}$ less than 82m.