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ENGINEERING OF
THE WASTE COMPARTMENT

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TECHNICAL NOTE 71.2

Bioreactor Design

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1. Introduction

The liquefying compartment of the MELiSSA loop is responsible for the biodegradation of human faecal material and other wastes generated by the crew. The volatile fatty acids and ammonia produced during the anaerobic fermentation process are fed to the second photoheterotrophic compartment inoculated with the bacterium *Rhodospirillum rubrum*. The produced CO_2 is supplied to the photoautotrophic compartment inoculated with the algal strain *Arthrospira platensis* and to the higher plants compartment.

At the pilot plant of the University of Barcelona, the three compartments of the MELiSSA loop (photoheterotrophic compartment CII, nitrifying compartment CIII and photoautotrophic compartment CIVa) are already connected at lab scale and will be validated at pilot scale. In order to validate the whole MELiSSA loop, it is necessary to construct the first compartment at pilot scale (fermentation reactor) for the primary degradation of the waste produced by the crew.

This technical note includes the conceptual design of the fermentation reactor and the filtration unit with a listing of the of sensors actuators, and allocation of interfaces (Figure 1).

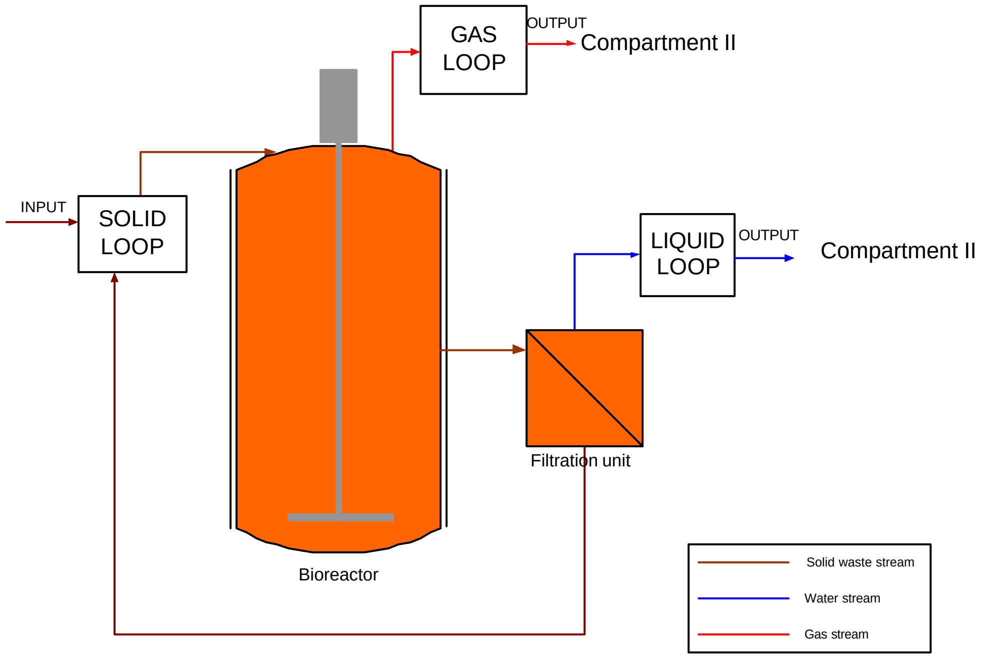


Figure 1: Schematic general design of the waste compartment with indication of the sub-system treated in this technical note

2. Concept of the fermentation reactor

2.1 Requirements of the reactor and filtration unit

The fermentation reactor is responsible for the degradation of the waste coming from the crew, like faecal material, inedible plant material and toilet paper. The reactor contains autochthonous anaerobic bacteria, which convert the waste, mainly into carbon dioxide, ammonium and volatile fatty acids. The reactor will be operated at 55°C (thermophilic conditions) and at a pH of 5.8 to 6 to avoid methane production, because the latter has no beneficial use in the further loop.

The products of the bacterial conversion of organic matter, found in the form of ammonia and volatile fatty acids need to be separated from the non-biodegraded matter before entering the second compartment. This will be done using a membrane filtration system. Membrane filtration is a technique that separates solid particles from solutes. The pore size of the membrane determines the quality of the permeate. The size of the particles in the reactor needs to be lower than 1 mm to avoid clogging of the membrane modules in the filtration unit.

2.1.1 Operation mode

Up till now the lab-scale reactor was operated in fed-batch mode. For the prototype and pilot reactor, the operation mode need to be determined, which can be batch, fed-batch or (semi-)continuous mode.

2.1.2 Stirring

In order to obtain a good contact between bacteria and waste material, the reactor need to be stirred. The reactor shape and the stirring regime are very important to avoid dead zones, and also accumulation of the waste material and clogging of the reactor's connections with the different sub-systems such as the filtration unit.

2.1.3 Process follow-up

The reactor will be equipped with several on-line sensors to provide local control and monitoring of the process parameters. The process parameters like temperature and pH should be accurately controlled. The accuracy, response time, maintenance requirements and calibration needs of the on-line sensors are important criteria for the selection of the material. The location of the sensors and the sampling method need to be determined. Moreover, it is important to define the selection criteria for each sensor and to make a trade-off to select the most appropriate sensor for the defined system. It is however, not in the scope of this study to make a final trade-off and selection of the instrumentation of the bioreactor. This will be reported in technical note 71.7.

2.2 General concept

2.2.1 Bioreactor

For the bioreactor, a liquid volume of 100 litres will be used. The reactor itself will be a cylindrical reactor with removable top. All the necessary fittings for sensors en connections to the adjacent sub-systems will be foreseen. The necessary connections needed are determined in technical notes 71.3 (solid loop design), 71.4 (liquid loop design) and 71.5 (gas loop design).

2.2.2 Filtration module

As mentioned above, a membrane filtration system is used to separate the solid particles in the reactor content from the dissolved components. A conceptual design scheme of the filtration system is depicted in Figure 2.

The filtration module is fed from a buffer tank using a circulation pump. The pump is able to build up a considerable trans-membrane pressure in the modules. This membrane pressure is monitored using three pressure sensors/transducers in the inlet and the outlet of the filtration module en in the filtrate produced. It is controlled by a pressure control valve in the return flow to the buffer vessel. A flow sensor is installed to in order to check the correctness of the desired recirculation flow rate. The amount of filtrate produced is checked using a scale. The correct amount, equal to the feeding flow rate of the bioreactor, is withdrawn and sent to the liquid loop. The rest is recirculated back to the bioreactor. The filtration module is designed such that the obtained filtrate flow is larger than the feeding flow rate to the bioreactor.

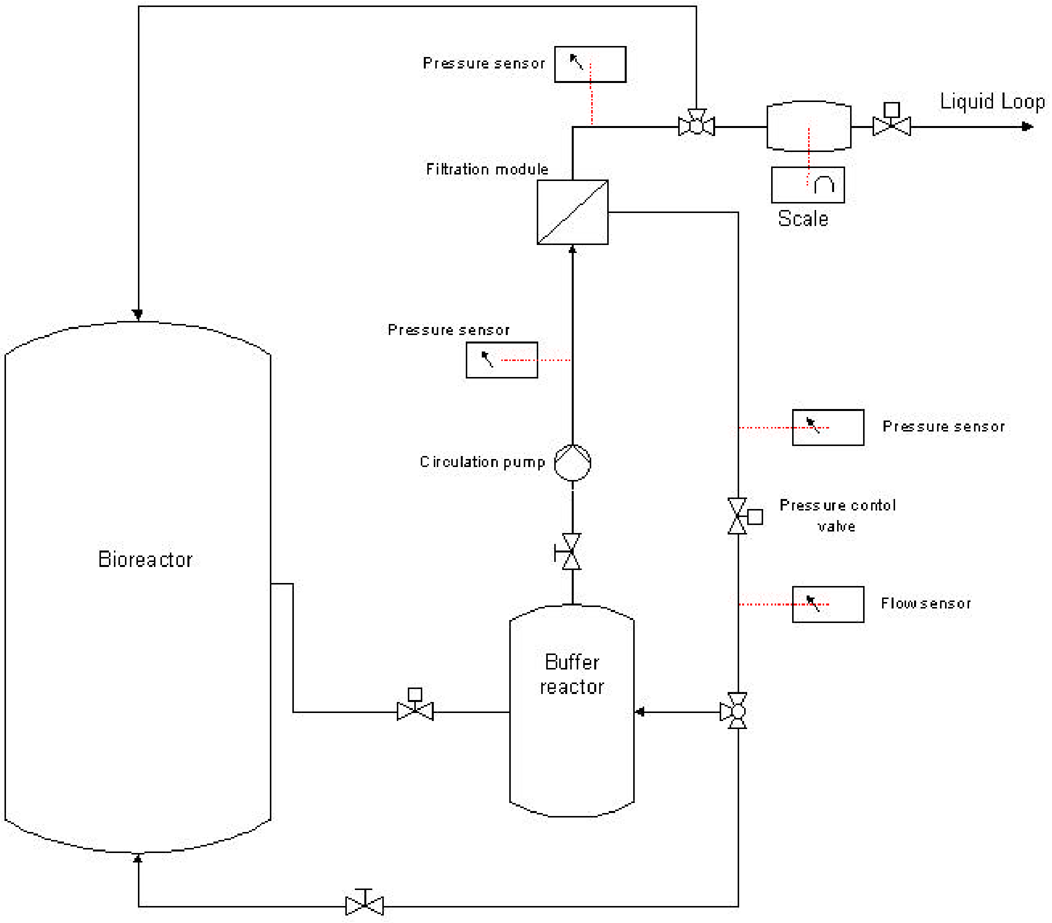


Figure 2: Conceptual scheme of the filtration system of the waste compartment

3. Review of hardware and instrumentation

3.1 Selection of tubing material

Requirements:

- resistant to corrosion
- resistant to biofilm formation
- resistant to chemical desinfection
- non permeable (air tight)

Generally the following statements can be made:

1. Metals are non permeable, but mostly sensitive to corrosion. Special steel types and alloys show an increased resistance to corrosion. The most commonly used material is stainless steel (AISI-316). Other materials will be discussed in chapter 3.2.4.

2. Polyvinyl chloride (PVC) is lightweight, chemical and water resistant. It is easy to use and install and it is an economic solution. The disadvantage of PVC is its lower temperature resistance on the long term. However, for PN16 tubing, a life time of 25 year is guaranteed at 4 bar and 60 °C.

3. The most inert material is glass. However, the limited compatibility of glass with pressure would cause the glass tubing to break.

Based on these findings a combination of stainless steel tubing with PVC tubing will be selected. Special care will be taken to connect the tubing in a proper way to the bioreactor, dependent on the bioreactor material selection.

3.2 Selection of bioreactor material

3.2.1 Introduction

The selected material for the bioreactor will have to meet certain requirements. These requirements are:

- Robust
- Corrosion proof
- Heat- and pressure-proof
- Resistant to chemical sterilisation
- As little are possible biofilm formation

Three different materials were taken into consideration for the construction of the reactor: polymers, stainless steel and glass.

3.2.2 Glass

DURAN is a borosilicate glass. DURAN glass used in laboratories and industrial plants has excellent chemical and physical properties. The glass has the following composition:

- 81% SiO_2
- 13% B_2O_3
- 4% Na_2O/K_2O
- 2% Al_2O_3

Borosilicate glass is highly resistant to water, acids, salt solutions, organic substances and halogens such as chlorine and bromine. It has also relatively good resistance to alkaline solutions. Only hydrofluoric acid, concentrated phosphoric acid and strong alkaline solutions cause appreciable surface removal of the glass at higher temperatures. The glass can be sterilised with hot air or steam.

It is however fragile, it cannot be subjected to abrupt changes in temperature and its resistance to pressure is limited. Furthermore, it is difficult to handle and to adapt in term of addition of connectors and fittings

3.2.3 Polymers

Two types of polymers can be distinguished: amorphous and crystalline polymers.

AMORPHOUS POLYMERS: e.g. PVC, Acrylic have:

- a wide melting range,
- low shrinkage after molding,
- Lower chemical resistance than crystalline polymers,
- Moderate heat resistance,

CRYSTALLINE POLYMERS: e.g. Polyethylene (PE), Polypropylene (PP) have:

- a sharply-defined melting point,
- high shrinkage after molding,
- high heat resistance,
- good fatigue endurance,
- good chemical resistance,

Polymers are generally easy to glue and/or solder.

3.2.3.1 PVC

Polyvinyl chloride (PVC), is made up of 40% petroleum and 60% salt. The characteristics of polyvinyl chloride make it suitable for a great number of products. PVC is water resistant, resists decay quite well and is lightweight. PVC's characteristics provide many benefits:

- High strength and durability
- Easy fabrication and use
- Thermoforming
- Dimensional stability
- Easy cleaning
- Economical

Disadvantages are however the moderate temperature and chemical resistance, especially towards solvents.

3.2.3.2 PP

Polypropylene is a long chain polymer made from propylene monomers. Several different polymerisation methods are used to produce polypropylene. Polypropylene have excellent heat resistance and can be used in continuous processes at temperatures as high as 104 °C (Figure 3).

In general, polypropylene is not susceptible to environmental stress cracking, and it can be exposed under load in the toughest environments. Due to its high crystallinity, polypropylene has excellent moisture barrier properties and good optical properties. High crystallinity improves stiffness, but reduces impact strength.

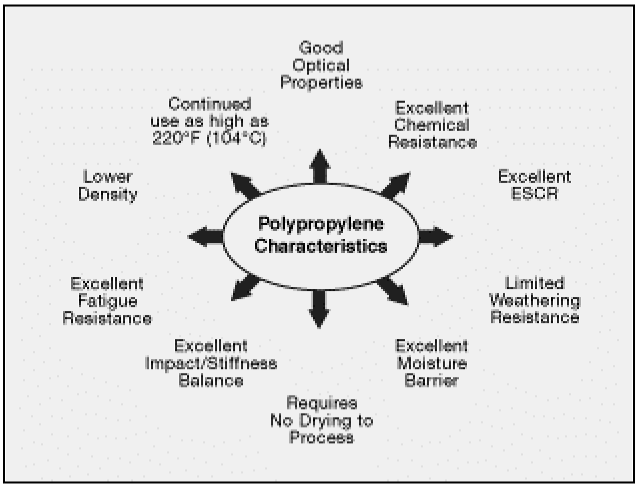


Figure 3: Characteristics of PP

3.2.3.3 PE

Polyethylene is commercially available in 5 grades, where the higher density PEs are more crystalline in nature:

- High density (HDPE)
- Low density (LDPE)
- Linear low density (LLDPE)
- Very low density (VLDPE)
- Ultra high molecular weight (UHMWPE)

It should be noted that even the high-density PE, has only a low to moderate temperature resistance.

3.2.3.4 Chemical resistance of the polymers

In Table 1, the chemical resistance is compared for PVC, PP and PE

Table 1. Chemical resistance of 4 different polymers

	PVC	**PP**	**PE**
Resistant to	Acids, bases	Acids, bases and weak solvents	
Not resistant to	Solvents, aromatics	Oxidative acids, halogens	

3.2.3.5 Chemical disinfectants for polymers

The chemical disinfectants are generally liquid solutions or alcohols containing special anti-microbial substances and tensio-active agents. The latter, due to their capillary effect, increase the bactericidal effect. Despite the fact that pH varies slightly during the desinfection, this does not have any influence on the resistance capacity of the plastic material. However, in case a polymer is used for the reactor construction, care should be taken with the selection of the disinfectant, since certain polymers can be sensitive to them.

3.2.3.6 Temperature resistance of polymers

Table 2 shows the temperature resistance for PVC, PP and PE.

Table 2. Temperature resistance for 4 different polymers

Material	**Maximal admissible temperature (°C)**	
	Continuous	**Batch**
PVC-C (extra-chlorinated)	90	110
PVC-U (Unplastified)	60	60
PP-HT (High Temperature)	90	100
PE-HD (High Density)	60	80

3.2.3.7 Conclusion

The maximal operating temperature of PVC -U and PE is 60°C, which is close to the working temperature of the reactor (55°C) and therefore, this type of polymers can not be used for the construction of the bioreactor in which a heating element of over 60 °C is present. Furthermore, the chemical resistance of PVC -U and PVC -C towards solvents is rather low.

PP is the most suitable polymer for bioreactor construction at slightly elevated temperature. However, care should be taken in selecting the eventual chemical disinfectant.

3.2.4 Metals/Alloys

The most commonly used metals/alloys for reactors are stainless steel, carbon steel, monel, hastalloy C and Titanium. A short description of the metals/alloys is given below:

3.2.4.1 Stainless steel

Stainless steel is an alloy of iron, chromium, nickel, carbon, and other materials. The various types possess different mechanical and physical properties. These properties are, in most instances, vastly different from low carbon (mild), medium carbon and low alloys steels, with a corresponding effect on the cutting methods and procedures.

Categories of stainless steels:

- **Austenitic -** A family of alloys containing chromium and nickel (and manganese and nitrogen when nickel levels are reduced). These alloys are not hardenable by heat treatment. This group offers the highest resistance to corrosion.
- **Ferritic -** This group of alloys generally containing only chromium, with the balance mostly Fe. These alloys are somewhat less ductile than the austenitic types and again are not hardenable by heat treatment.
- **Martensitic -** The members of this family of stainless steels may be hardened and tempered just like alloy steels. Their basic building block consists of 12% Cr, 0.12% C, and balance mostly Fe.
- **Precipitation-Hardening -** These alloys generally contain Cr and less than 8% Ni, with other elements in small amounts. As the name implies, they are hardenable by heat treatment.
- **Duplex -** This is a stainless steel alloy group, or family, with two distinct microstructure phases, ferrite and austenite. The Duplex alloys have greater resistance to chloride stress corrosion cracking and higher strength than the other austenitic or ferritic grades.
- **Cast -** The cast stainless steels, in general, are similar to the equivalent wrought alloys. Most of the cast alloys are direct derivatives of one of the wrought grades. The alloy is primarily used for resistance to liquid corrosion.

The advantages and disadvantages of the different types of stainless steel are summarised in Table 3.

Table 3. Advantages and disadvantages of the different applicable types of stainless steel

Type	Examples	Advantages	Disadvantages
Ferritic	410, 430	Low cost, moderate corrosion resistance & good formability	Limited corrosion resistance, formabilty & elevated temperature strength compared to austenitics
Austenitic	304, 316, 317	Widely available, good general corrosion resistance, good cryogenic toughness. Excellent formability & weldability	Work hardening can limit formability & machinability. Limited resistance to stress corrosion cracking
Austentic	254 SMO	High resistance to pitting an crevice corrosion, very high resistance to chloride stress corrossion	Work hardening can limit formability & machinability.

If the selected metal material will be of stainless steel, the choice will be between stainless steel 316 (which is widely available), 317 or 254 SMO dependent on the need to resist corrosion (mainly by Cl^-). It should be noted that stainless steel AISI-316 is an industry standard for easy interfacing, an proven technology for sensor fittings (which are mostly in 316L/PVDF).

3.2.4.2 High-carbon steels

High-carbon steels are extremely strong but more brittle and therefore harder to form and weld. This composition however allows better responses to heat treatment and longer service life than medium-carbon steels. High-carbon steels have superior surface hardness resulting in high wear resistance. The AISI designations for High-carbon steel are: AISI 1055-1095, 1137-1151, and 1561-1572

3.2.4.3 Monel 400

Monel 400: A combination of approximately 68% nickel and 28% copper. This alloy has superior resistance to oxidation and corrosion and provides excellent service in sea or brackish water.

3.2.4.4 Hastalloy C

Hastalloy C: A combination of nickel, chromium, molybdenum, iron, and tungsten. This alloy performs well at elevated temperatures in the range of 1600° to 1800° Fahrenheit (871°C to 982°C).

3.2.4.5 Titanium

Titanium: A silvery metallic chemical element; very malleable and ductile. Its principal function has been as an addition to steel to create steel alloys, but now is being used in its pure form (100% titanium) because of its high strength, light weight, and good corrosion resistance.

3.2.5 Conclusion

- Due to its fragility and low pressure tolerance, glass is not recommended for the reactor construction.
- PP can only be used if the reactor will not be steam sterilised. Chemical disinfection is possible with certain chemicals. Polymers are easy to glue and solder and are light in weight.
- The problem with any metal and any alloy is corrosion. However, with the selection of the proper steel type, this problem can be avoided. The advantages are a high temperature and pressure resistance, a long life time and the possibility to include industry-standard sensor fittings and interfaces.

Based on these findings, a reactor constructed in stainless steel is preferred. Since no elevated Cl^- concentrations are to be expected, stainless steel AISI-316 can be used. Corrosion due to the gas composition is also not expected due to the absence of O_2 in the head space of the reactor. H_2S itself is not corrosive towards stainless steel AISI-316 without the presence of O_2.

3.3 Reactor shape and mixing

3.3.1 Mixing

The following requirements can be listed for a good mixing of the bioreactor

- Low abrasive power on biomass;
- Suspension of relatively low density solids in the reactor;
- Good homogenizing capability;
- Relatively low mixing intensity (tip speed < 2 m/s) so low power input (< 200 W/m^3).

According to these requirements, an LC-impeller was selected for the following reasons:

- A good balance between homogenizing and micro-mixing is obtained;
- More turbulence is generated than with a standard marine propeller;
- It is ideal for suspension of solids (a pumping effect via axial flow is generated);
- Low abrasive power via limited rotation speed of max. 250 rpm. (via variable speed drive)

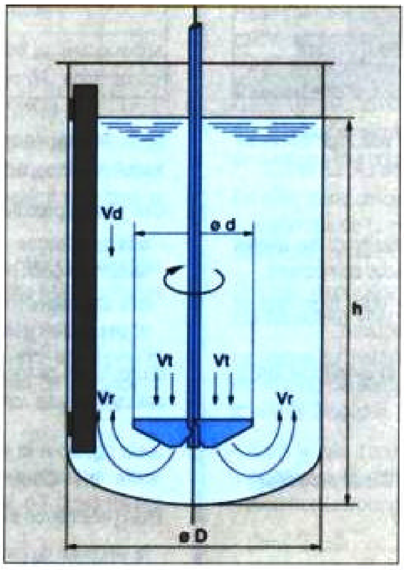
The connection of the mixer to the reactor will be done via a flange and a lip seal for air tightness.

3.3.2 Resulting reactor shape

Large-scale anaerobic digestion tanks are either cylindrical, rectangular or egg-shaped. The most common design is a low, vertical cylinder. Rectangular tanks are used infrequently because of the greater difficulty of mixing the tank content uniformly. The floor of the reactor is usually conical with a minimum slope of 1 vertical to 4 horizontal. The purpose of the egg-shaped design is to eliminate the need for cleaning and to have a better mixing.

For the small-scale bioreactor of EWC, the shape is largely dependent on the mixing properties. When an LC-impeller is installed, the following guidelines should be followed for a cylindrical reactor (Figure 4):

- $d/D = 0.5 \rightarrow 0.7$
- $h/D = 2$
- height from bottom = $d/2 \rightarrow d$



Vt = fluid discharge velocity
Vr = lifting velocity
Vd = settling velocity

Vt = vitesse de traversée
Vr = vitesse de remontée
Vd = vitesse de décantation

Figure 4: Guidelines for the dimensioning of reactor shape and impeller

For the pilot bioreactor with a liquid volume 100 l, the following dimensions are selected:

D = 40 cm, h = 80 cm, impeller size 25 cm

Furthermore, baffles are needed to avoid a vortex in the reactor. Vortexing causes a reduction in the difference between the fluid velocity and the impeller velocity and thereby decreases the effectiveness of mixing. The usual method is to install four or more vertical baffles extending approximately one-tenth the diameter out from the wall. These baffles break up the mass rotary motion and promote vertical mixing. The proposed dimensions are:

- baffle size = 0.1 x D = 4 cm

3.3.3 Resulting quantities

Based on the dimensioning developed above, some quantities can be calculated in order to check the proper reactor set-up:

Axial flow:

- Total pumped flow by the impeller = 4.2 l/s
- Lifting velocity v_r = 8.5 cm/s
- Sedimentation velocity << Lifting velocity, so no sedimentation will occur.

3.4 Phase separation and filtration

Due to the high content of solids (2,5%), preference was given to a side-stream MBR concept, which means that the digester (reactor) and the membrane part are separated. The content of the digester is pumped over the membrane module in cross-flow mode. The cross-flow velocity causes turbulences at the feed side of the membrane so that concentration polarization phenomena and fouling can be controlled.

3.4.1 Membrane filtration

The following description is based on the dimensions of the final pilot bioreactor (± 100 l) and a residence time of 10 days corresponding to a flow rate of 10 l/day. The solids in the reactor can have a concentration of maximum 5%. The size of the solids needs to be lower than 1 mm to avoid clogging of the tubes in the membrane module. In Figure 5, the concept of the proposed membrane filtration unit (MFU) is presented.

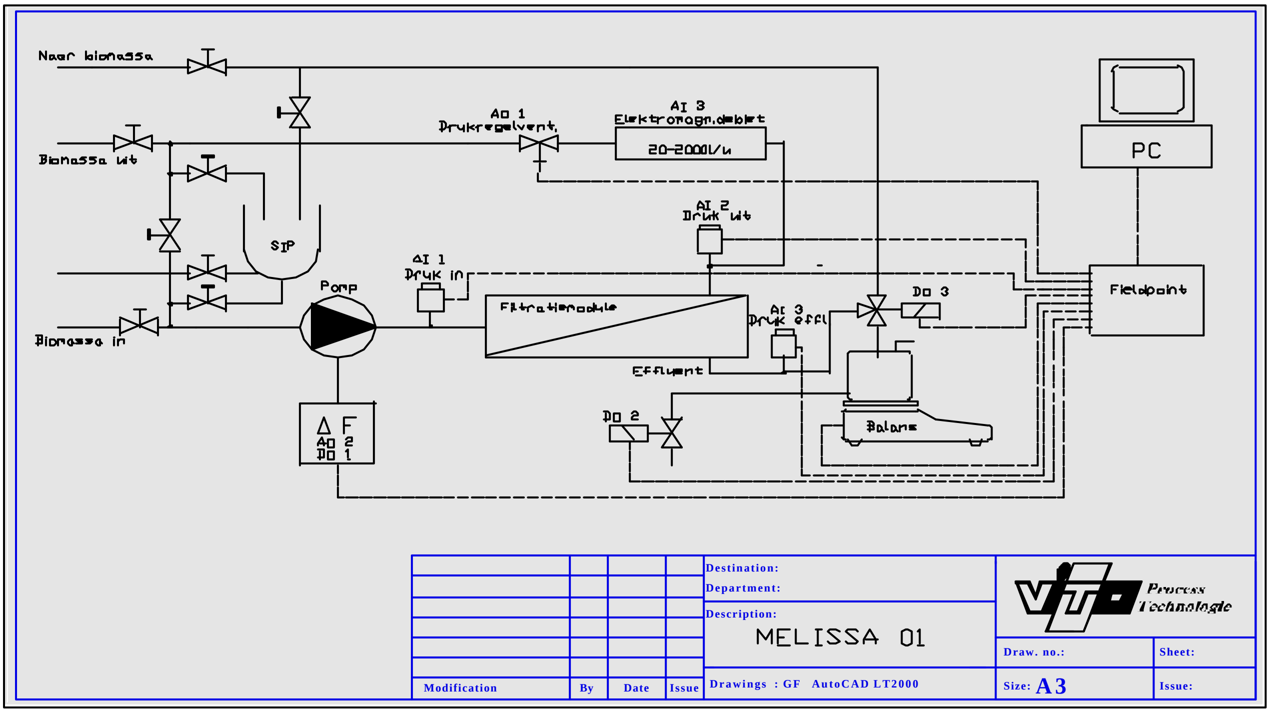


Figure 5: Membrane filtration unit (MFU) for the waste compartment

The MFU is designed with a (frequency steered) feed pump with a maximum capacity of 1 m³/h at 4 bar. The unit is equipped with all necessary transmitters and valves for accurate process control, as indicated in Figure 5. This instrumentation will be further discussed in paragraph 3.7. The permeate collector is connected to a three way valve: the permeate is either collected on a balance and is sent to the liquid loop before entering the second compartment or, when fluxes are too high, part of the permeate is sent back to the bioreactor.

The filtration module itself consists of one single F5385 PVDF membrane tube with a diameter of 8 mm and with adjustable length, with a maximum of 1 m (length of 1 m corresponds to 0.025 m² of membrane surface). If necessary, the pump is capable to feed a second membrane module, which can be placed either in serial or in parallel. A cross-flow velocity of 4 m/s corresponds to a pump flow of 724 l/h, which means that the entire content of the digester is pumped over the membrane module more than 7 times in one hour. A bypass is foreseen in the concentrate stream (the concentrate is the stream which returns to the digester) so that part of the recycling can be done over the bypass instead of over the digester. The connection tubes are designed at a diameter of 12 mm.

3.5 Feeding regime

3.5.1 Batch

Batch fermentation refers to a partially closed system in which most of the materials required are loaded onto the fermentor, before the process starts and then, removed at the end. The only material added and removed during the course of a batch fermentation is the gas exchange and pH control solutions. In this mode of operation, conditions are continuously changing with time, and the fermentor is an unsteady-state system, although in a well-mixed reactor, conditions are supposed to be uniform throughout the reactor at any instant in time.

3.5.2 Fed-batch

In a fed batch reactor, the micro-organisms are fed on a regular base (ex. Once a day) after taking the same amount from the reactor.

The fed-batch technique was originally devised by yeast producers in the early 1900s to regulate the growth in batch culture of *Saccharomyces cerevisiae*. Yeast producers observed that in the presence of high concentrations of malt, the by-product ethanol was produced, while in low concentrations of malt, the yeast growth was restricted. The problem was then solved by a controlled feeding regime, so that yeast growth remained substrate limited.

3.5.3 Continuous

Continuous culture is a technique involving feeding the micro-organism used for the fermentation continuously with influent and, at the same time, removing effluent from he system. An unique feature of the continuous culture is that a time-independent steady-state can be attained which enables the determination of the relations between microbial behaviour (genetic and phenotypic expression) and the environmental conditions.

3.5.4 Conclusion

A continuous or semi-continuous feed regime is selected for the bioreactor, since this is the most stable operation mode. It also allows the filtration unit to work continuously, which is needed for proper operation of this unit.

3.6 Pumps

3.6.1 Introduction

The waste compartment will be equipped with pumps in order to transport the feed and the reactor liquid. Depending on the flow and the material that needs to be transported, a type of pump will be selected.

3.6.2 Influent pump

3.6.2.1 Membrane pump

Advantage:

- Membrane pumps are very precise (used for dosing of liquids) and can pump low volumetric flow rates.

Disadvantages:

- Require maintenance (periodic replacement of the membrane heads)
- Expensive

3.6.2.2 Peristaltic pump

Peristaltic pumps offer several advantages over other type of pumps. They also require maintenance, but the most significant advantage is that the only wetted material is the tubing. This makes the maintenance easier and cleaner compared to membrane pumps.

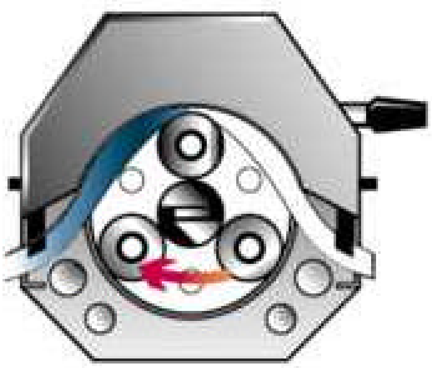


Figure 6: Peristaltic pumphead

3.6.2.3 Conclusion

For reasons of easy maintenance and cleanliness, a peristaltic pump will be selected for the (semi)continuous feeding of the bioreactor.

3.6.3 Recirculation pump

In order to recirculate the reactor content over the filtration unit, a progressive cavity pump is selected. This was done for reasons of low shear rate, high viscosity and possible presence of sand particles in the solution. Furthermore, centrifugal pumps with the same capacity are generally not capable of a continuous pressure build-up of 4 bars, as is required in the filtration system.

Progressive cavity pumps are a type of rotary, positive-displacement pump. The unique characteristic of this design is the special configuration of the two main pumping elements and their respective relationship within each shaft rotation. The moving element is a single external helix that is circular in its cross section. It also maintains an eccentric motion as it rotates. This is called the rotor. The stationary pumping element has a double internal helix.

The helices are 180° opposed with a pitch length that is twice as long as the pitch length of the single helix rotor. When this stationary element, the stator, is combined with the rotor, cavities are created. As the rotor revolves, these cavities progress in a spiral motion through the pump. Two complementary cavities are formed, so as one cavity is finishing its cycle another is beginning its cycle.

This results in an uninterrupted, continuous flow of material through the pumping elements. Because of the compression fit between the rotor and stator these discrete cavities are positively sealed. The sealing lines defining the cavities will hold pressure even when the pump is not rotating. Because these cavities are completely sealed, positively isolating the suction and discharge conditions from each other, the pump is capable of high suction lifts and high pressures, independent of its operating speed.

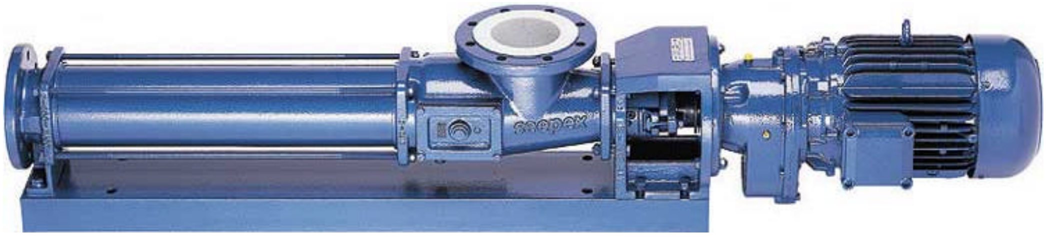


Figure 7: Picture of progressive cavity pump

3.7 Process instrumentation

3.7.1 Introduction

The reactor will be equipped with several on-line sensors to provide local control and on-line monitoring of the most important process parameters. The reactor will contain the following sensors: pressure, level, temperature, pH, redox, EC and solids. An alkalinity analyser will not be installed as the pH measurement and a logging of the amount of acid (or base) added gives already good indication of the chemical buffer capacity of the reactor content. Moreover, also the electroconductivity (EC) measurement is considered as an optional measurement as the MELiSSA feed does not have a high salts content.

3.7.2 Pressure

The pressure inside the reactor and at different locations in the filtration unit is measured with pressure transducers. For the pressure ranges under study (0 to 5 bar), pressure transducers with a ceramic or silicon membranes can be used. The pressure to be measured causes a small deflection of the c diaphragm of the sensor. A change in capacitance proportional to the pressure is measured by electrodes on the sensor. This way, gauge or absolute pressure can be measured.

These pressure transducers are stable, easy to install, and come with an internal transmitter generating a 4-20 mA output signal. Examples of such sensors are the Endress+Hauser Cerabar T PMC 131 (ceramic membrane) or the SensorTechnics PTE2000 series (silicon membrane). Several versions of the latter can be ordered for use in e.g. the reactor (0-0.34 bar or 5 psi) and the gas loop (0-5 bar, see TN 71.5)

3.7.3 Level

3.7.3.1 Introduction

The level of the reactor can be controlled using a level sensor. Common principles used to monitor water levels are: floats with an internal electric switch, conductivity switches, differential pressure transducers, ultrasonic level detection, radar level detection, RF admittance and capacitance measurements (Figure 8). The two first techniques are only useful for on/off level detection. The others give a continuous signal.

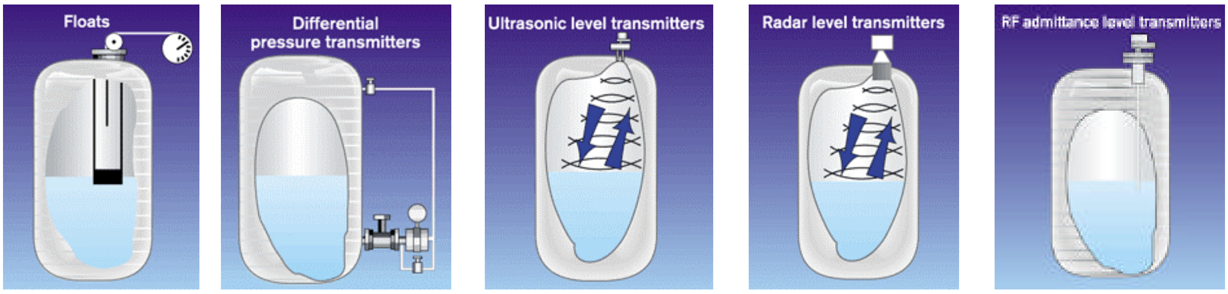


Figure 8: Different types of level sensors

3.7.3.2 Differential pressure level sensor

Differential pressure transmitters (DP) are probably the most frequently used measurement for level detection. A differential pressure transmitter is used to transmit the head pressure that is due to the height of the material in a tank. This pressure multiplied by the density of the material gives an indication of the level in the tank.

Advantages:

- Adequate for small vessels
- Ease of installation, maintenance (can be installed externally)
- Good precision

Disadvantages:

- Interferences: changing liquid density, pressure waves in the fluid
- Initial calibration needed
- Vessel penetration close to the bottom

Testing with the lab scale reactors, showed that a density increase of about 10 g/L is to be expected when the dry matter content in the reactor increases with 20 g/L. This is the maximal dry matter increase that can be expected when periodical draining is performed.

A density increase with 10 g/L is equivalent to a 78.5 Pa pressure increase at the bottom of the reactor. This, in turn, is equivalent to a level difference of about 0.8 cm en a total volume difference of 1L (or 1%), when the nominal liquid level is 80 cm. This error can be tolerated in the bioreactor without an influence on the process conditions.

Pressure waves are not to be expected in the reactor, since a relatively low mixing intensity is used. Furthermore, vessel penetrations close to the bottom is needed anyway for the insertion of other sensors (pH, ORP, ...).

3.7.3.3 Ultrasonic level sensor

Ultrasonic transmitters work on the principle of sending a sound wave from a piezo electric transducer to the contents of the vessel. The device measures the length of time it takes for the reflected sound wave to return to the transducer. A successful measurement depends on reflection from the process material in a straight line to the transducer.

Advantages:

- No contact with process material
- No moving parts

- No calibration needed
- Single top of vessel entry

Disadvantages:

- Various interferences: foam, surface turbulence, vapors, ambient noise, ...
- Not suitable for small-scale applications

3.7.3.4 Radar level sensor

Two technologies are on the marked: frequency modulated continuous wave (FMCW) or pulsed wave time of flight. Pulsed wave systems emit a microwave burst towards the process material, this burst is reflected by the surface of the material and detected by the same sensor. Level is inferred from the time of flight. GMVW systems, however, continuously emit a swept frequency signal and distance is inferred from the difference in frequency between the transmit and receive signals.

Advantages:

- No contact with process material
- No moving parts
- No calibration needed
- Single top of vessel entry
- Highly accurate

Disadvantages:

- Expensive
- Less suitable for small-scale applications

3.7.3.5 Capacitance

A capacitor is formed by a sensing probe and a ground plane (usually the tank wall). The instrument measures the amount of process material present by measuring how much energy will flow from the probe to "ground" (virtual or earth) due to the capacitance effect. More energy flows as the elevation of the material between the probe and ground increases. The energy flow is directly proportional to the material elevation, and is used to produce a mADC output signal, or a precise switching action.

Advantages:

- Works at extreme pressure and temperature
- Only one vessel penetration

Disadvantages:

- Problems with media that coat the sensing element (fouling)
- Initial calibration needed
- Only suitable for clean, water-like media

3.7.3.6 RF admittance

RF admittance works similar to a capacitance transmitter, with two circuit additions. By measuring the resistance and capacitance of any coating to the sensing element, the error generated by a coating can be measured and corrected for.

Advantages:

- Works at extreme pressure and temperature
- Very versatile
- Only one vessel penetration

Disadvantages:

- Quite expensive
- Initial calibration needed

3.7.3.7 Conclusion

Based on the above findings, only two measurement techniques are suitable for this application of a small-scale reactor filled with anaerobic sludge: differential pressure transmitters and RF admittance level sensors. Differential pressure transducers are a lot cheaper than the RF admittance type sensors. However, they are more sensitive towards small disturbances and possibly fouling. The main advantage of DP's is the ease of installation, maintenance and replacement. Therefore, a differential pressure transducer will be tested at the prototype stage and its performance will be evaluated. This will be done using SensorTechnics PTE2000 series pressure transducers.

3.7.4 Temperature

3.7.4.1 Introduction

The temperature is a critical measurement in the anaerobic biodegradation process. It needs to be controlled to maintain a stable temperature of 55°C. A fluctuation in temperature can cause a disturbance in the bacteria population.

3.7.4.2 Platium resistance thermometer

The function of a restistance temperature detector (RTD), is based on the fact that the electrical resistance increases with increasing temperature. The main metals used for this purpose are Pt, Ni or a Ni-alloy. In particular Pt has a stabile and reproducible relation between temperature and resistance. Pt-sensors are normalised, especially the Pt100, a Pt-sensor with an electrical resistance of 100 ohm at 0°C is abundant in Europe. Its advantages include chemical stability, ease of manufacture, the availability of Pt-wire in highly pure form and an excellent reproducibility of its electrical characteristic. Pt100 sensors are recommended where superior accuracy is needed over thermocouple accuracy, mainly in the temperature range between –50 °C to 200 °C

3.7.4.3 Thermocouples

A thermocouple is a pair of conductors of dissimilar materials joined at one end and forming part of an arrangement using the thermoelectric effect for temperature measurement. This thermoelectric effect is the production of an electromotive force, due to the difference of temperature between two junction of different metals of alloys forming part of the same circuit. Different letters are designated to thermocouple wire combinations. Extension cables should only be used when supplied by the manufacturer with the same nominal composition as the thermocouple. The Type-T thermocouple (Copper/Copper-Nickel) is widely used to measure low temperatures and in applications where moisture is present.

3.7.4.4 Conclusion

Generally Thermocouples are more subject to measurement errors and have a lower accuracy compared to Pt100 sensors. They are also harder to install correctly. Therefore Pt100 sensors will be used for temperature monitoring and control.

3.7.5 pH

3.7.5.1 Introduction

Next to temperature, pH will be controlled, since this parameter is also crucial. To avoid methane production, the reactor needs to be operated at a pH lower than 6.

3.7.5.2 Glass electrode

In the glass-electrode method, the difference in pH between solutions inside and outside a thin glass membrane creates electromotive force in proportion to this difference in pH. This thin membrane is called the electrode membrane. Normally, when the temperature of the solution is 30 °C, if the pH inside is different from that of outside by 1, it will create approximately 60 mV of electromotive force.

The liquid inside the glass electrode usually has a pH of 7. Thus, if one measures the electromotive force generated at the electrode membrane, the pH of the test solution can be found by calculation.

A pH meter consists of a glass electrode, a reference electrode, and a temperature-compensation electrode. Mostly composite electrodes are used, in which these are integrated into one unit. The glass electrode itself consists of an electrode membrane that responds to pH, a highly isolating base material to support the unit, solution inside the glass electrode, an internal electrode, a lead wire, and a glass electrode terminal. Generally, silver chloride is used as the material for the internal electrode. Potassium chloride solution maintained at pH 7 is usually used as the internal solution.

Standard industrial electrodes for pH measurements in water and wastewater are filled with a KCl gel (0% silver ions) instead of a liquid solution. This guarantees longer stability times. However, calibration is still needed at regular time intervals. The frequency of calibration will be determined during the follow-up of the prototype reactor, which is running at EPAS. Normally, one calibration every week should be sufficient. At least, the electrode should be checked weekly, and calibration should be performed when a significant difference is found in measuring the buffer solutions at pH 4 and 7.

pH sensors can be purchased at several companies like KNICK, WTW, Endress+Hauser...

3.7.6 Redox Potential (ORP)

3.7.6.1 Introduction

The redox measurement can verify the anaerobic conditions of the reactor and gives also indications to control nitrate and nitrite content.

3.7.6.2 Method

ORP is a potentiometric measurement in which the potential (or tendency) of the medium for electron transfer is sensed by an inert metal electrode and read relative to a reference electrode that is immersed in the same medium. This determination can also be referred to as a "redox" measurement (combination of REDuction and OXidation). For most multi-parameter monitoring systems, the inert metal electrode is a button or ring made of platinum and the reference electrode is the same one associated with the pH sensor, usually Ag/AgCl. The readout of the sensor is a voltage (relative to the reference electrode), with positive values (e.g., + 300 mV vs. Ag/AgCl) indicating an oxidizing environment (ability to accept electrons) and negative values (e.g. -300 mV) indicating a reducing environment (ability to furnish electrons).

ORP sensors can be purchased at several companies like KNICK, WTW, Endress+Hauser... Calibration of an ORP electrode is needed at regular time intervals, that can be determined experimentally for each case of use.

3.7.7 EC

EC indicates how much dissolved salt is in the medium that is measured. EC is measured by an EC meter or solubridge. The sensor passes a weak electric current from one pole and measures the strength of the current received at the other. The sensor used looks like a pH meters, where the glass bulb electrodes are replaced by metal prongs or bridges in order to measure the electrical current passing between them. EC is measured in mS/cm (milliSiemens per centimeter).

Conductivity sensors can be purchased at several companies like KNICK, WTW, Endress+Hauser...

3.7.8 Solids

The on-line measurement of solids is based on the measurement of turbidity (Figure 9). Depending on the construction and the measurement principle of the probe, a wide range of turbidity and solids contents can be measured. Depending on the probe type, either light absorption of scattered light is measured. The light sources are usually monochromatic LEDs with a wavelength in the infrared region. In order to compensate for fouling and soiling of the probe, temperature changes, ambient light and the aging of optical components, different photodetectors can be used and their signals can be placed in relation to each other.

Different probes can be obtained for immersion or for pipe installation. Their main features are:

- Robust design, stainless steel construction
- No moving parts
- Auto compensation for soiling and aging
- Choice between suspended solids content or turbidity reading

Figure 9: Turbidity Meter

3.7.8.1 On-line measurement of solids content in the reactor

The measurement of solids in the high concentration ranges is based on the principle that the intensity of incident light is attenuated proportionally to the concentration of solids contained in the medium. The difference between incident and captured light is used for the measurement, according to the Lambert-Beer Law (Figure 10).

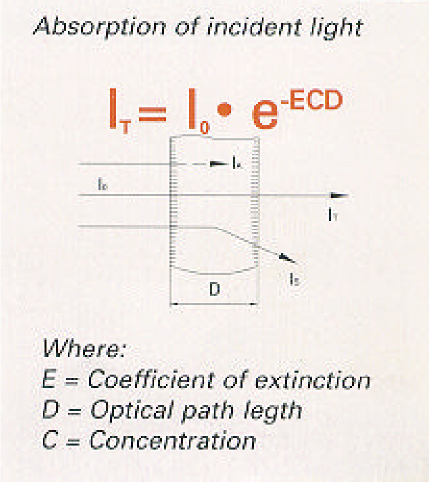


Figure 10: Lambert-Beer law

An example of such on-line solids measurement is the Staiger Mohilo StamoSens 7100 with a StamoSens 7520 SAV probe. In activated sludge systems, a sludge concentration up to 60 g/l can be measured.

3.7.8.2 Effluent turbidity measurement

The membrane material of the filtration unit has very small pores in the range of nanometers. Thus, UF removes viruses, bacteria, other micro-organisms, non-dissolved materials and larger dissolved molecules. Despite the fact that the resulting liquid from the filtration unit is supposed to be exempt from contaminating particles (bacteria, viruses, macroelements, ...), safety measures should be taken. The liquid stream originated from the filtration unit could therefore be controlled for its content in insoluble compounds through the use of a suspended solids monitor. This is also done by measuring turbidity, but now in the low concentration range. This is done by measuring scattered light. The principle used to do this is the Tyndall effect (Figure 11). Accordingly, the intensity of the scattered light is proportional to the number of suspended particles. If it is carefully set up, this approach is very sensitive and permits detection of small degrees of turbidity.

Nevertheless, reflections from the vessel walls can adversely affect measurements at low turbidity levels. It is especially important to take this into account. The distance between the probe and the nearest wall should be large enough to avoid wall effect problems. Alternatively, it should be taken into account in the calibration procedure.

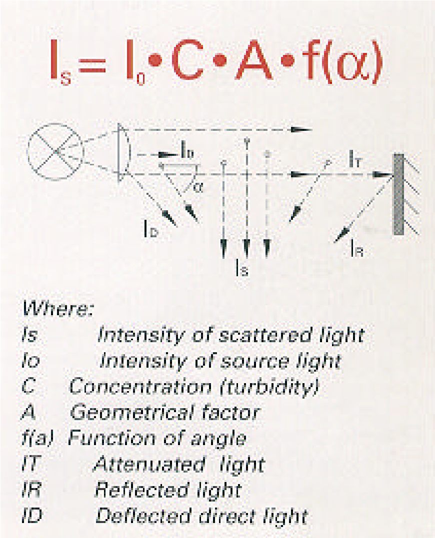


Figure 11: Tyndall effect for light scattering

An example of such on-line solids measurement is the Staiger Mohilo StamoSens 7100 with a StamoSens 7530 SSN probe.

3.7.9 Flowmeter

In order to measure and control the flow circulating through the filtration unit, a flow meter is installed There are different types of flowmeters: electromagnetic, coriolis, vortex and ultrasonic. Furthermore, in order to precisely measure the produced effluent flow, a scale will be used.

3.7.9.1 Electromagnetic flowmeter

Faraday's law of induction states that a voltage is induced in a conductor moving in a magnetic field. In electromagnetic measuring, the flowing medium corresponds to the moving conductor. The induced voltage is proportional to the flow velocity and is detected by two measuring electrodes and transmitted to the amplifier. Flow volume is computed on the basis of the pipe's diameter. The constant magnetic field is generated by a switched direct current of alternating polarity.

Advantages of electromagnetic flowmeters are their high measuring accuracy, the possibility to install them on tubes with a wide diameter range and thereby measure a wide range of flow rates. They also have a low pressure drop and are able to measure bi-directionally.

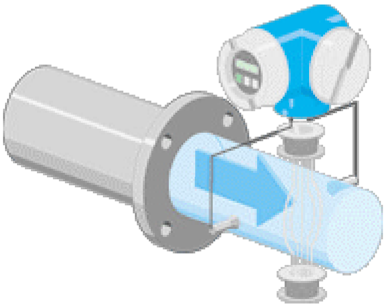


Figure 12: Principle of an electromagnetic flowmeter

3.7.9.2 Coriolis flowmeter

A mass flow dependent Coriolis force occurs when a moving mass is subjected to an oscillation perpendicular to the flow direction. The measuring system accurately determines and evaluates the resulting effects on the measuring tubes.

Coriolis flowmeters also have a high measuring accuracy and can measure bi-directionally. The pressure drop is larger compared to electromagnetic flow meters. They are more suited to measure flow rates in applications with a high liquid density.

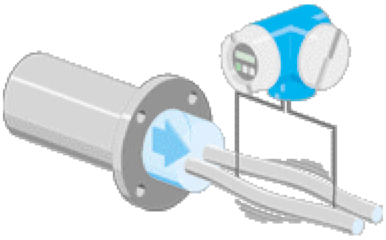


Figure 13: principle of a coriolis flowmeter

3.7.9.3 Vortex flowmeter

Vortex flowmeters operate according to Karman's vortex street principle. Vortices are created and alternate behind a bluff body. The number of vortices shed per time unit, the vortex frequency, is directly proportional to the flow rate. These flowmeters are especially interesting for measuring flows in high temperature and pressure conditions.

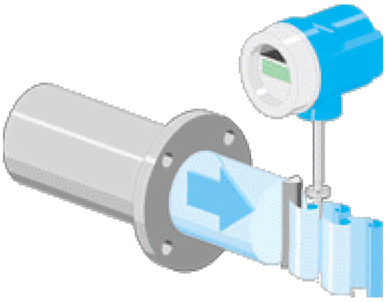


Figure 14: Principle of vortex flowmeter

3.7.9.4 Ultrasonic flowmeter

Prosonic Flow operates on the principle of transit time differences. An acoustic signal (ultrasonic) is transmitted from one sensor to another. This can be either in the direction of flow or against the direction of flow. The time (transit) that the signal requires to arrive at the receiver is then measured. According to physical principles, the signal sent against the direction of flow requires longer to return than the signal in the direction of flow. The difference in the transit time is directly proportional to the velocity of flow. Ultrasonic flowmeters are mostly used for retrofitting, since they can be installed externally. This compensates for their lower accuracy compared to electromagnetic flowmeters and they lower measurement range.

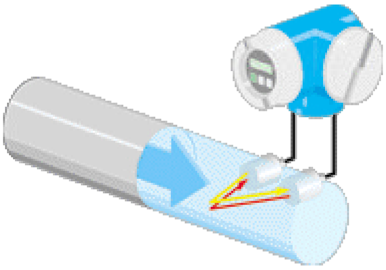


Figure 15: Principle of ultrasonic flowmeter

3.7.9.5 Conclusion

For the situation under study, an electromagnetic flowmeter is most suitable. For the flow used in the filtration unit (up to 700 l/h), an Endress+Hauser Promag 50DN08 was selected.

3.7.9.6 Scale: Sartorius BP 1200

In order to precisely measure and control the produced effluent flow after filtration, a scale is used. A Sartorius BP 1200 with serial output was selected for this purpose.

3.7.10 Alkalinity

3.7.10.1 Introduction

Alkalinity is a measurement of the capacity of water to neutralize acid. The significant of alkalinity is that it acts as pH buffer in treatment process for water and wastewater. The alkalinity of many surface waters is primarily a function of *bicarbonate*, HCO_3^-, *carbonate*, CO_3^{2-}, and *hydroxide*, OH^-. Other salts of weak acid may be present in small amounts.

3.7.10.2 Example

An example of an on-line alkalinity monitor is Hach's APA 6000 Alkalinity Process Analyzer. It is a microprocessor-controlled process analyzer designed to continuously monitor total and phenolphthalein alkalinity. The analyzer combines titrimetric and colorimetric methods of detection to determine alkalinity.

This type of sensor is rarely used in wastewater treatment because quite some information on the buffer capacity can be gathered combining the pH measurement with a logging of the amount of acid (or base) added to the reactor. Therefore this sensor is considered optional.

3.7.11 Viable Biomass monitoring

The range of Aber Biomass Monitors can be used in bioreactors for the measurement of viable bacteria, yeast, animal, plant and other cellular biomass. Cells can be measured whilst in a free suspension, in solid substrates, or immobilised on inert carriers such as glass beads or micro-carriers (Figure 17).

Cells with intact plasma membranes in a fermentor can be considered to act as tiny capacitors under the influence of an electric field. The non-conducting nature of the plasma membrane allows a build-up of charge. The resulting capacitance can be measured; it is dependent upon the cell type and is directly proportional to the concentration of these viable cells. In the probe four electrodes are used to apply a radio frequency field to the biomass (Figure 16). Electronic processing of the resulting signal produces an output which is an accurate measurement of the concentration of viable cells.

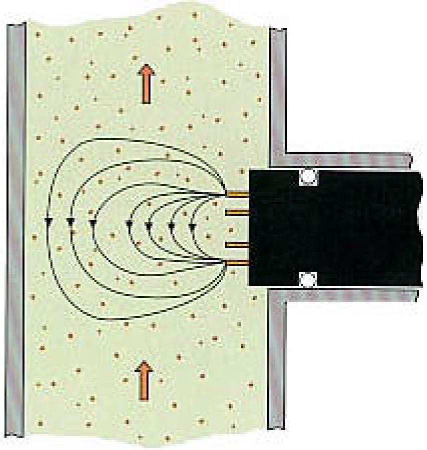


Figure 16: Flow of yeast suspension in pipe work past the Yeast Monitor Probe

The system is responsive to viable cells and is insensitive to cells with leaky membranes, gas bubbles and cell debris. Unlike conventional optical measurement techniques, high biomass concentrations can be measured with the Biomass Monitors. The system can be expanded with a multiplexer. The fluid operating temperature range is 3 to 60°C.

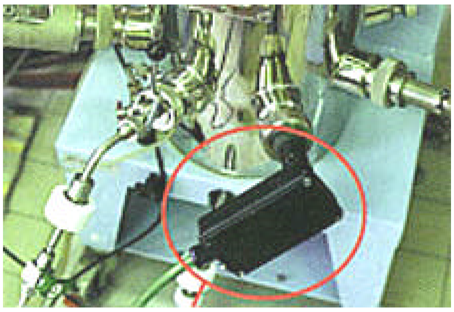


Figure 17: Biomass probe fits as standard 25mm Ingold type port.
19mm top entry is also available.

3.8 Temperature control

3.8.1 Introduction

The bioreactor will be operated at a temperature of 55°C. This temperature needs to be constant to obtain constant environmental conditions and therefore to avoid shifting in the microbial community. A cooling/heating system has to be supplied to maintain the temperature of 55°C. The reactor can be equipped with a double jacket, a heating spiral or a direct heating element can be inserted in the reactor.

3.8.2 Double jacket

When a double jacket is used, a heater circulator is used to recirculate warm water through the double jacket. This heater contains water and needs to be filled up on a regular base.

Advantages:

- No element in reactor, therefore no deposition of material
- Robust, easy exchange of parts (heating, pump)
- Easy control, safe

Disadvantages:

- Addition of water to the unit on a regular base

3.8.3 Heating spiral

Also a heating spiral in the reactor can be used with an external heat exchanger.

Advantages:

- Practically same advantages as double jacket, but
- Easier connection of fittings, sensors

Disadvantages:

- Presence of element in reactor, therefore possibility of deposition of material and lowering of efficiency
- Addition of water to the unit on a regular base

3.8.4 Heating element

A heating element can also be introduced in the reactor or implemented as a coat outside the reactor.

Advantage:

- No liquid necessary
- Easy connection of fittings, sensors

Disadvantage:

- Presence of element in reactor, therefore possibility of deposition of material and lowering of efficiency
- Higher risk for overheating, less reliable
- Electrical component in close contact with reactor content

3.8.5 Conclusion

Based on the findings above, it was decided to use a double jacket reactor with an external heater (eventually cooler) and heat exchanger when a stainless steel reactor is chosen. Only part of the reactor needs to be covered since the needed capacity is rather small. Only a capacity of about 50 W is needed to keep the reactor at its desired temperature. However, a higher heating capacity is needed at start-up, since the reactor content needs to be warmed up to 55 °C within a reasonable time scale. For the heating of 100 litres from 20 °C to 55 °C within 2 hour, a capacity of about 2 kW is needed.

3.9 Fittings and connections

3.9.1 Tri-weld / Tri-Clamp

Tri-weld fittings (Figure 18) will be used to weld interface ports onto the reactor, in order to connect the reactor with different subsystems. Tri-clamp fittings are used to connect different tubings together. Elbows, Tees, concentric reducers (to connect a larger and smaller sized pipe) are available in several sizes.

Figure 18: Fittings welded onto a reactor

Tri-clamp connections offer quick coupling action. They are made of stainless steel. They are fast and easy to take down, provide leak-tight connections and are readily adaptable to other forms of piping. Available in 1"-4" (25.4mm - 101.6mm) tube OD sizes and material type 304, 316 or 316L. Standard finish 1"-4" (25.4mm - 101.6mm) fittings are polished to 32Ra., No. 3 polished ID/non-polished OD or No. 1 non-polished ID/OD finishes are available.

3.9.2 Ingold ports and housings for sensor fitting

Sensors will be mounted onto the reactor. Some sensors will be installed on the side of the reactor. A housing system will serve as an enclosure for the sensors. The industry standard for connecting thes housings to the reactor are the Ingold ports. The housings themselves can be provided retractable for sensors that need cleaning and calibration and also not retractable (Figure 19).

Figure 19: Picture of an INFIT fitting

3.9.2.1 Mettler Toledo: Infit 764

Technical specification:

- Not Retractable
- Pressure range: 0 to 6 bar
- Mounting: Weld-in socket internal Ø 25 mm, Thread: G 1 1/4”, 1 1/4” NPSM
- Weight: InFit 764: ~ 2 kg

3.9.2.2 Mettler Toledo: Infit 776/777/797

Technical specification:

- Retractable (manual or pneumatically) without interrupting or shutting down the on-going process
- Pressure range: 0 to 6 bar
- Mounting: Weld-in socket internal Ø 25 mm, Thread: G 1 1/4”, 1 1/4” NPSM

Suitable for pH, ORP, turbidity, conductivity

4. Disinfection and cleaning

4.1 Introduction

A proper cleaning and disinfection of the system needs to be possible before start-up and after shutdown of the system. Sterilisation of the reactor itself is not considered useful, since a mixed culture of bacteria is grown inside the reactor. However, it should be clear that it is the aim to produce a sterile effluent. The way this is achieved is further treated in technical note TN71.4.

4.1.1 CIP (Cleaning In Place) procedure

4.1.1.1 Pre-rinsing

In this step, the surfaces to be cleaned are rinsed with water. Pre-rinsing removes some debris and reduces the need for chemicals. Warm or hot water is used because the solubility of many components of the debris is greater at higher temperatures. However, if excessively hot water is used, there is a risk of "cooking on" debris. Microbial biofilms and/or mineral deposits will remain on the equipment after this pre-rinsing step.

4.1.1.2 Chemical Cleaning:

Cleaning chemicals are intended to lift debris from the equipment surface and keep it suspended in water so that it can be rinsed away. No single cleaning chemical does this effectively under all conditions. Instead, mixtures are used.

- **Water**

  The cornerstone of chemical cleaning is water. Ideally, the water should be low in hardness minerals. Hard water inhibits the ability of some cleaning compounds to suspend debris and can result in mineral deposits on equipment surfaces.

- **Surface Active Agent (Surfactant)**

  The major ingredient in most mixtures is a surfactant. Its function is to suspend debris components that normally do not stay suspended in water. Of the three types of surfactants, anionic, nonionic, and cationic, the anionic surfactants are most commonly used.

- **Acid or Alkali**

  One or more compounds will be included to adjust the pH of the cleaning solution. Acidic cleaners are very useful for removing mineral deposits. Chlorinated alkaline cleaners are used for removing many different types of debris and work especially well against high-protein debris. It is recommended to proceed with the cleaning in a cycle acid - alkaline and if needed again acid.

- **Water Softeners**

  Some cleaning mixtures will contain components, called either water softeners or chelators, that chemically bind water hardness minerals. Examples of chelators include certain polyphosphates, gluconates and EDTA.

Critical factors for the success of this cleaning are the correct temperature and concentration of the chemicals. Furthermore the contact time is of importance as is the pressure and the force associated with the application of the cleaning solution. Therefore, special nozzles are designed in order to increase the effectiveness of the treatment. During CIP, the nozzle head is forced from its retracted position to the CIP position via compressed air. The nozzle is rotated by the cleaning liquid pressure and sprays cleaning fluids over the entire surface area of the reactor.

Figure 20: an example of CIP nozzles

4.1.1.3 Rinsing

Once chemical cleaning is done, the cleaning mixture and suspended debris are removed by rinsing. Rinsing should be thorough and is done with warm water to prevent debris from being re-deposited.

5. Design proposal

5.1 Introduction

In the previous chapters an overview of the components necessary to construct a bioreactor and a filtration unit (including materials, sensors, fittings, valves, pumps, mixing of the reactor,...) is given. Here a schematic overview of the hardware and its position in the system is given (Figure 21, Figure 22, Table 4, Table 5 and Table 6).

5.2 Reactor design and instrumentation

Table 4. Reactor design

Item	**Value and description**
Material	Stainless Steel AISI-316 wall thickness 3 mm
Liquid volume	100 litres
Total reactor volume	125-130 litres
Operating temperature	55 °C via double jacket (dimplates)
Operating pressure	100 mbar
Reactor dimensions	Diameter (D): 400 mm Height liquid column (h): 800 mm Total height reactor: 1000 mm
Reactor construction	Spherical top and bottom DIN 28011 Removable top part via flange DN400
Mixing	Mixing intensity: 150-200 W/m^3 Impeller at 250 rpm with diameter (d): 25 cm Gas-tight sealing 3 baffles in reactor: 4 cm width
Instumentation at the bottom	2 * temperature probe 2 * pH electrode (via InFit777 on Ingold port) 1 * ORP electrode (via InFit777 on Ingold port) 1 * conductivity (EC) (via InFit 764 on Ingold port) 1 * pressure transducer 1 * turbidity measurement 2 * Ingold ports (supernumerary)
Connections at the bottom	2 * sampling ports 1 * ball valve for emptying reactor 3 * TriWeld/TriClamp fitting (connection with filtration unit) 1 * TriWeld/TriClamp fitting (feed) 2 * TriWeld/TriClamp fitting (supernumerary)
Instrumentation at the top	1 * pressure transducer
Connections at the top	1 * pressure relief valve 4 * connection with gas tubing (gas loop connection) 1 * connection with gas tubing (supernumerary) 1 * port for gas sampling 2 * connections for pH adjustment

Table 5. Reactor instrumentation

Reference	**Description**	**Type**	**Sub-type**
BL-R-001	Mixer for the bioreactor, equipped with LC-impeller	Motor	
PD-R-001	Precision stainless steel pressure transmitter bioreactor	Transducer	Sensor Technics PTE2005G (4A), 0-0.34 bar or 5 psi
TT-R-001	Temperature transmitter	Transmitter	
TT-R-002	Temperature transmitter	Transmitter	
TS-R-001	Temperature sensor	Sensor	PT100, -50 °C up to 250 °C
TS-R-002	Temperature sensor	Sensor	PT100, -50 °C up to 250 °C
pHS-R-001	pH sensor	Sensor	Gel filled pH electrode
pHS-R-002	pH sensor	Sensor	Gel filled pH electrode
pHT-R-001	pH transmitter	Transmitter	
pHT-R-002	pH transmitter	Transmitter	
ORPS-R-001	ORP sensor	Sensor	Potentiometric
ORPT-R-001	ORP transmitter	Transmitter	
LS-R-001	Level sensor	Sensor	Differential pressure, using 2 PTE2005G transducers
LT-R-001	Level transmitter	Transmitter	
ECS-R-001	Conductivity sensor	Sensor	Solubridge
ECT-R-001	Conductivity transmitter	Transmitter	
SS-R-001	Suspended solids sensor	Sensor	Turbidity sensor via light transmission
ST-R-001	Suspended solids transmitter	Transmitter	
HX-R-001	Heat exchanger	Heater	capacity 2 kW
BS-R-001	Viable biomass monitor (optional)	Sensor	Capacitive probe
AS-R-001	Alkalinity monitor (optional)	Sensor	Titrimetric sensor

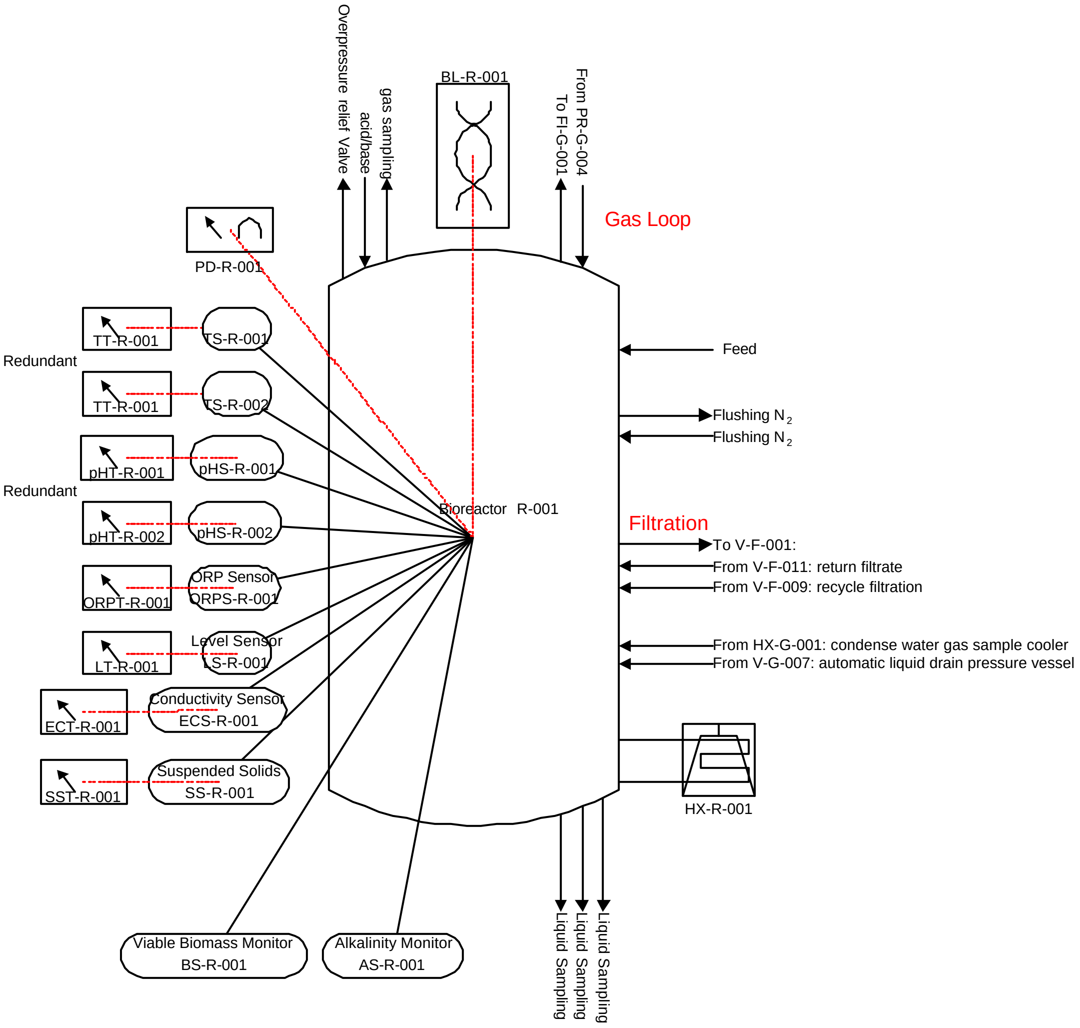


Figure 21: Conceptual drawing of the reactor instrumentation

5.3 Filtration unit design and instrumentation

The filtration unit will consist of one single membrane tube with a diameter of 8 mm. The membrane is a microfiltration membrane (F5385 PVDF: 8 mm x 1 mm).

Table 6. Filtration unit design and instrumentation

Reference	**Description**	**Type**	**Sub-type**
V-F-001	Valve for control of filtration module feeding	Pneumatic control valve	Bürkert 2000 A 20,0 RVS
V-F-006	Control valve for transmembrane pressure	Pneumatic control valve	Kämmer 20037
V-F-011	2-way valve for regulating effluent recirculation to bioreactor	Solenoid valve	Bürkert 6014
V-F-013	2-way valve for regulating effluent recirculation to bioreactor	Solenoid valve	Bürkert 6013
TS-F-001	Temperature sensor in the filtration loop	Endress+Hauser sensor	TST42, 0 – 100 °C
TT-F-001	Temperature transmitter	Endress+Hauser iTemp	TMT187
LD-F-001	Level Switch	Endress+Hauser Liquiphant T	FTL 260
SS-F-001	Suspended solids sensor	Sensor	Turbidity sensor via light scattering
ST-F-001	Suspended solids transmitter	Transmitter	
PD-F-001	Pressure transducer with ceramic membrane	Endress+Hauser Cerabar T	PMC 131, 0 – 6 bar
PD-F-002	Pressure transducer with ceramic membrane	Endress+Hauser Cerabar T	PMC 131, 0 – 6 bar
PD-F-003	Pressure transducer with ceramic membrane	Endress+Hauser Cerabar T	PMC 131, 0 – 6 bar
FD-F-001	Flow transducer for control of the flowrate through the filtration	Endress+Hauser Promag	50H80, 20 – 2000 l/h
WD-F-001	Scale for control of filtrate production	Sartorius	CP3202S
PMP-F-001	Pump for recirculation over filtration module, nominal flow rate 724 l/h (equivalent to cross-flow velocity of 4 m/s)	Progressive cavity pump	Seepex 2-12BN/A1-C1-C6-F0-A, 0 – 1 m^3/h

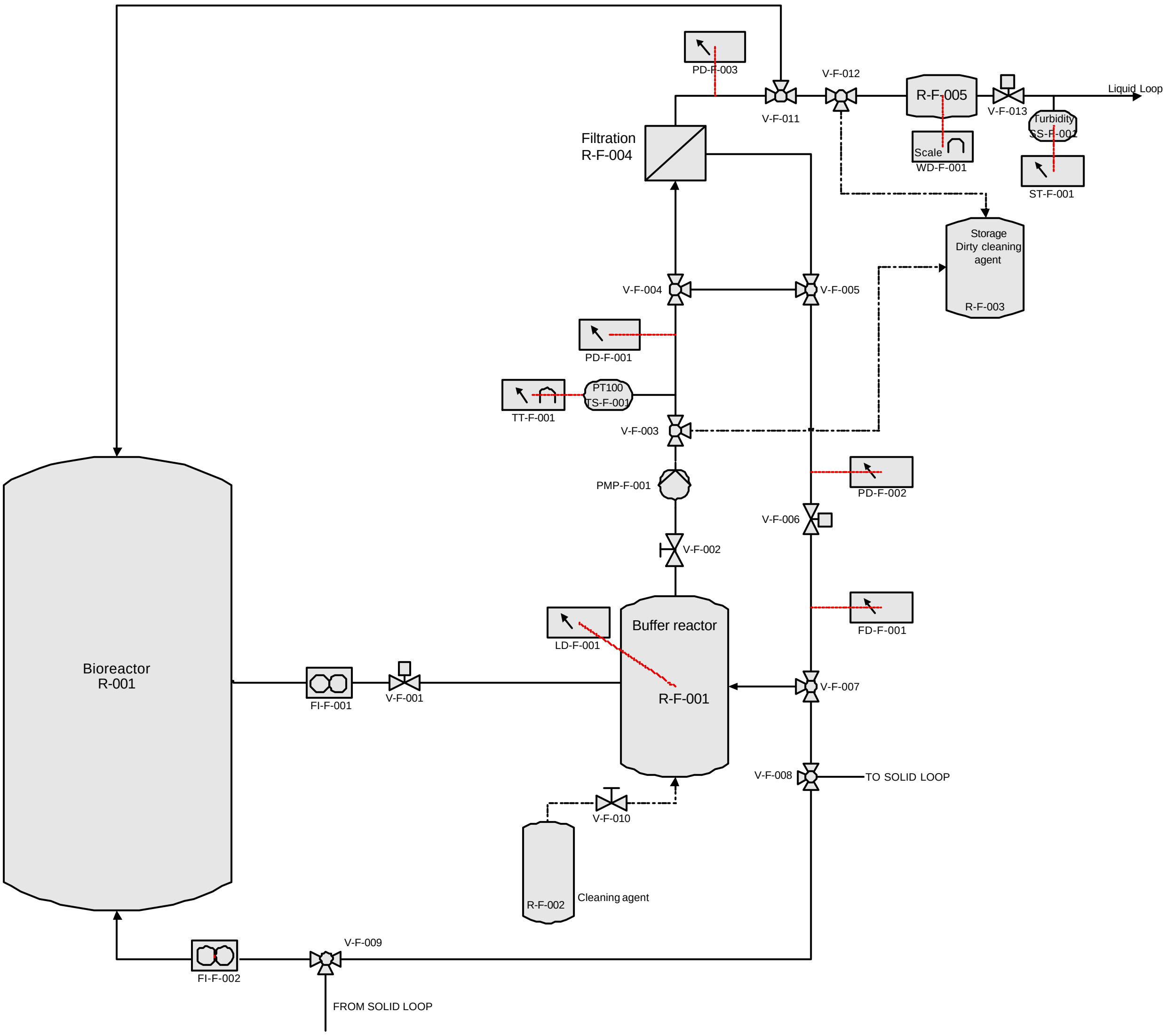


Figure 22: Conceptual drawing of the filtration unit

6. Local control aspects

Different levels of control will be applied in order to successfully control the reactor. These levels are local and supervisory control. Part of the supervisory control will be a model based control law. The control aspects of the waste compartment will be further elaborated in technical note TN71.8. In the following, a brief introduction will be given on the local control of the bioreactor and the filtration module.

6.1 Bioreactor

The local control of the filtration system is based on the following sensors:

- Temperature sensor (redundant);
- pH sensor (redundant);
- Turbidity sensor;
- Level sensor.

These sensors control the following actuators:

- A heat exchanger;
- A peristaltic acid/base addition pump;

Furthermore, the level sensor in the reactor indicates the necessary effluent flow rate of the filtration system. The reading from the turbidity sensor enables the operators to drain the reactor on regular time intervals.

6.2 Filtration module

The control of the filtration system is based on the following data:

- the transmembrane pressure calculated from the three pressure transducers in the system (inlet, outlet, filtrate);
- the flow through the filtration module measured using the flow sensor;
- the effluent flow measured using the scale in the filtrate line;
- A level switch in the buffer vessel.

These data control the following actuators:

- A pneumatic control valve;
- Several solenoid valves (two- and three-way);
- A frequency-controlled recirculation pump.

Recirculation occurs mainly through the buffer vessel and only partly through the bioreactor itself. This proportion is controlled using manual valves. The level in the buffer vessel is controlled using a level switch. If the level decreases, extra reactor liquid is fed to the buffer vessel by opening a solenoid valve.

The recirculation flow is kept constant using the measurement of the flow via the flow sensor. This way, the frequency controller is adjusted. The control strategy furthermore maintains a constant transmembrane pressure using the pneumatic control valve on the basis of the measured pressure.

The other solenoid valves control the effluent flow rate to the liquid loop. This effluent flow rate should be equal to the flow rate that is fed to the bioreactor. This flow rate should be fixed and this exact amount of filtrate is released to the liquid loop.

In the prototype reactor, this control is implemented using PC-software. For the pilot reactor, this software will be translated to run on the local PLC.