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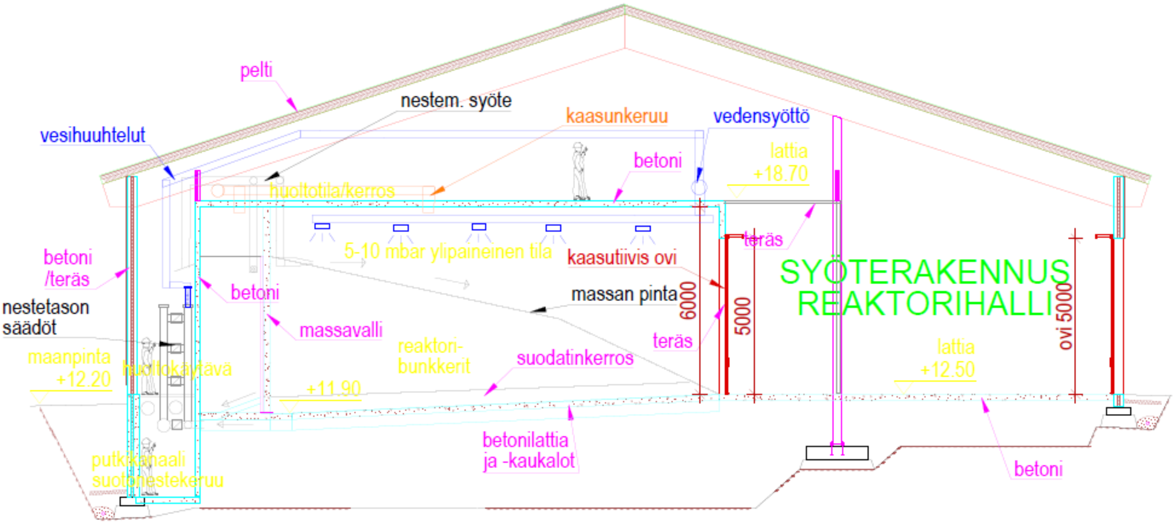
Farm Scale Biomethane Production Plant for Challenging Raw Materials



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1 INTRODUCTION

Demanding raw materials, such as agricultural and industrial residues which contain impurities like plastic have become of special interest among companies which are considering investing in new biogas plants. Although these materials seldom constitute the majority of feedstocks, there may be sufficient reasons to use them, reasons including gate fee, environmental protection and other similar drivers. The challenge is in removing these impurities before feeding the material into the reactor. There may be ways of separating these materials after the bulk has gone through the biogas production reactions, but more likely the impurities are thermally treated together with the solid biogas residues to provide energy for the main processes at the site.

This study focuses on the structure and features of a batch-type reactor specially designed for handling difficult feedstocks.

2 CHALLENGES INVOLVED

Any solid (or liquid except water) material which is not consumed in the biogas reactions is considered as an *impurity*. These include polymers such as plastics, as well as inorganic materials such as sand and metals. The plastics are particularly difficult, as the may have equal density as water, which means they cannot be removed by gravitational means. Strings which are used for supporting vegetables in production of cucumbers and tomatoes are a good example of such impurities, see Figure 1 for reference. They are usually cut to 5 to 10 cm pieces, which makes filtering them out from the organic mass very difficult.

Main challenge: plastic strings used to support the vegetables

Figure 1. Strings used for supporting the vegetables create a problem in biogas processes.

Plastic packaging is common in food industry. Sometimes it is possible to wash the organic material from the packages, but usually some of the packaging ends up in the feedstock.

3 DIFFICULT RAW MATERIALS

The difficult raw materials include but are not limited to:

- Argicultural residues (plastics)
- Poultry litter (sand and stones)
- Animal carcasses (bones)
- Fur animal manure (sand)
- Food wastes (domestic or industrial, plastics and others).

Sand and other heavy materials can sometimes be removed before feeding into the biogas process, and as they have a tendency to settle (heavier than water or biogas slurry), they can be removed as a separate fraction during reactor cleaning. Materials such as plastics do not decompose or otherwise participate in the biogas reactions. This means that they stay practically intact. As many of the organic materials in which the plastic comes with have a cell structure more or less the same size as the plastic strings or stripes, mechanical separation is nearly impossible.

4 WET AND DRY REACTORS

The two main types of biogas reactors are the *wet reactors*, in which the material forms a slurry and is mixed (practically a continuous stirred tank reactor *CSTR*), and *dry reactors* where the solids suspension density is higher and the material whether moves as a solid body (*plug flow reactor*) or is treated as a stagnant mass (*batch reactor*). See the difference illustrated in Figure 2.

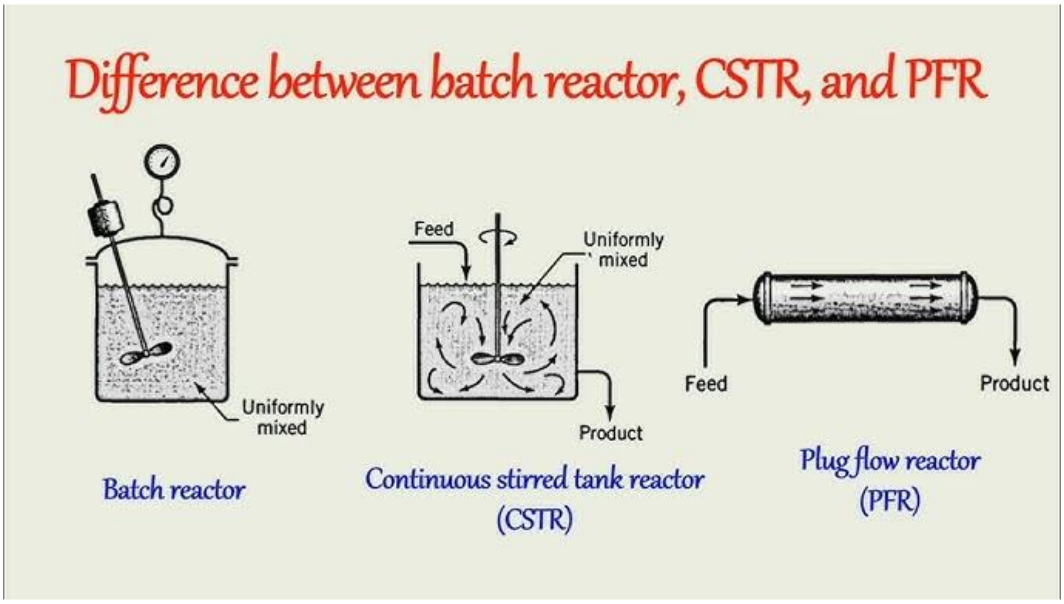


Figure 2. Difference between batch, continuously stirred tank and plug flow reactors.

In biogas production, batch reactors are used for such materials which form a solid-type structure and come in large quantities at a time, such as straw. The mixing is not done by moving the solid body itself, but introducing a bacteria-containing warm liquid called *percolate* which flows through the solids and keeps the reactions going. Liquid reactors can be fed and purged continuously, as well as the plug flow reactors. Wet reactors are not recommended for materials which contain impurities, as they are difficult to clean (the reactor needs to be emptied). Batch reactors with a stagnant solid reaction mass may be most efficient for plastics containing feedstocks.

6. SOLIDS CONCENTRATION AND BIOGAS PRODUCTION

As explained in the document *Biogas Plant Basic Design*, the solids content inside the reactor plays a major role. The traditional wet reactors operate in the range of 5 – 12 % solids. This is due to the increase in viscosity as the solids content in slurry increases, see Figure 3 for reference. Each organic solid provides an individual effect on the viscosity, so it is very hard to predict how a slurry is going to behave: only experience is a sufficiently accurate way to determine the maximal solids content. Main reasons for the viscosity/solids content limit is in mixing: the operating principle of a wet reactor should be as close to a CSTR as possible. Other issues are related to heat transfer and pumping: thick sludge is hard to pump through a heat exchanger pipe and the heat transfer is reduced if the flow is laminar, and the energy requirement for pumping increases significantly as the sludge thickens. Sauter-type (Figure A1 in *Biogas Plant Basic Design*) wet reactors have all the pumping, heating and mixing outside the reactor, so they may operate with a slightly increased solids content, up to 15 %.

Special mechanically mixed plug-flow reactors (Kompogas, BioGTS) have been developed to cope with the higher solid material contents, between 15 % and 30 %. When the solids content increases from this, the reactors are defined as real dry processes, where the material forms a fixed matrix. These reactors have a void (gas space) between individual solid particles. Figure 4 illustrates the distribution between solids, water and gas space.

The plan is to develop a reactor which operates in the dry region.

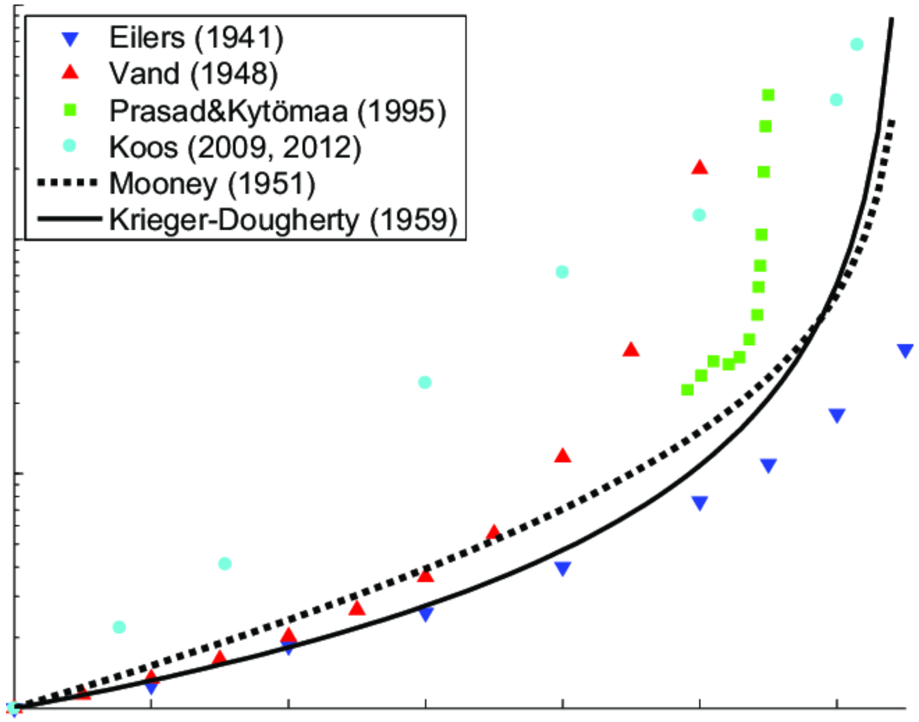


Figure 3. Viscosity increase as the solids content increases, biomaterial and water.

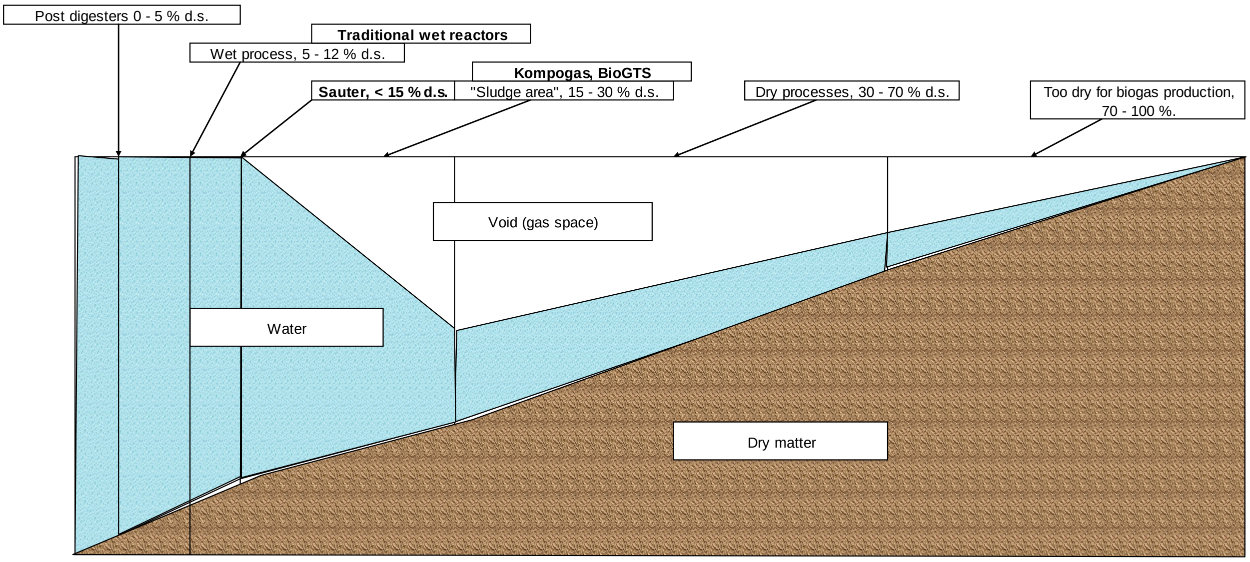


Figure 4. Illustration of the relation between solids, water and gas space in biogas production.

5 EXAMPLE REACTOR

A pre-study done by Gas1 Oy (formerly One1 Oy) has listed some of the possible features of a biogas reactor for difficult feedstocks. These include:

- Batch operation, each reactor is filled and emptied several times per year.
- Sloped bottom structure for forming a pre-designed solid bed structure.
- Use of percolate instead of mixing.
- Using the sloped bottom for gravitational transfer of the used percolate.
- Connection to a liquid reactor for production of percolate.
- Possibility to add a separate or integrated liquid reactor.
- Using the percolate for heating and even heat distribution.

Figure 5 shows an illustration (side view) of the system (some texts in Finnish).

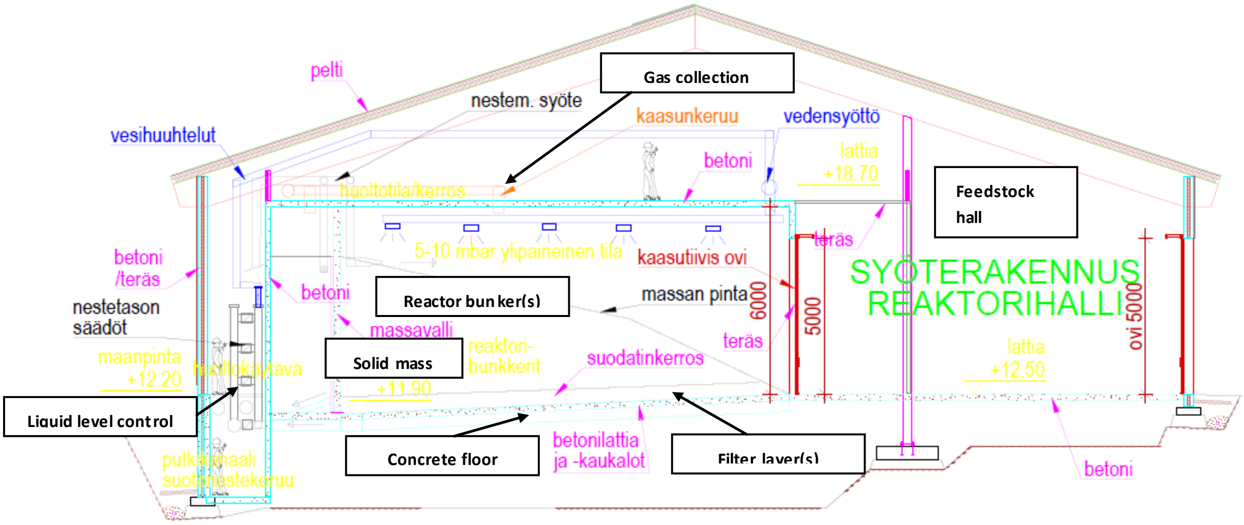


Figure 5. Illustration of a slope-bottom reactor for difficult biomasses.

One of the special features in the reactor is the use of filter layer(s) to allow the solid material to maintain the original structure while the percolate has more or less free path to the collection channels at the bottom. These filter layers can be pre-structured such as filter mats, or made at the beginning of each batch by adding straw or similar porous material.

The whole reactor structure has to be made gas-tight, which sets special demands especially for the door: there shall be a limit for the methane loss (*slip*) during operation set by the EU.

The percolate is a liquid of water and suspended bacteria, which means it may have a relatively high solids content. Pumping and heating of such mass requires special equipment. In turn, the nozzles used for distributing the liquid must be of special design.

If there is a risk of settling due to for instance sand in the liquid, all places where this sand can settle must be equipped with access for inspection and cleaning. Sand can also cause wear in moving components and erosion in bends, especially if plastic piping is used.

Finally, the monitoring of the process during operation needs to be designed in a manner that the flow and quality of the percolate can be measured reliably. Any information about the formation (height, density) of the solid bed could also be used for controlling the gas production.

So, there are several open questions to answer during the study. A survey on existing batch reactors could provide additional information about how similar challenges have been encountered in earlier projects, both domestic and abroad.

Biogas Plant Basic Design, Two Methods

Forward method	**Backward method**
Feedstocks are known (quantity and quality)	Energy demand sets the size
Calculation of biogas potential for each feedstock (may also be dynamic based on temporary feedstock maximum availability) and thus calculation of gas production.	Calculation of biogas/biomethane need.
Selection of process type (mesophilic, thermophilic, wet, dry process). Brings biogas yield and residence time.	Selection of process type (mesophilic, thermophilic, wet, dry process). Brings biogas yield and residence time.
Based on the average (or monthly max) feed, calculation of fermenter volume based on feedstock solids content, solids suspension density and residence time.	Calculation of biogas production based on available feedstocks. Fixing the feed matrix.
Dimensioning of feed system and auxiliaries.	Based on the average (or monthly max) feed, calculation of fermenter volume based on feedstock solids content, solids suspension density and residence time.
Basic engineering.	Dimensioning of feed system and auxiliaries.
	Basic engineering.

Feedstocks and Biogas Potential

The feedstocks for biogas production are carbon-based organic materials, which may originate from agriculture, food industry or other process handling these substances. The *biogas potential* is a parameter which tells how much the feedstock can produce biogas in optimal conditions, i.e. in most cases the theoretical maximum. As biogas is mainly formed from the carbon in the solid material, the carbon content is one of the main constituents in the biogas potential. High moisture content and impurities (inorganic materials such as sand) reduce the biogas potential.

Biogas potential can be expressed in unit [m^3_N/kg dry material] or [m^3_N/ton fresh material], the latter requiring also the solids content. In addition to the total biogas potential, the division between different components (mainly CH_4 and CO_2) can be shown.

Germany as the leading country for biogas production has developed a small database, which contains not only the biogas potentials for several substances, also some nutrient contents. Table A1 shows an example of such a database. The main groups in the database are:

- Animal Manures & Slaughter Wastes
- Grain and Grass Energy Crops
- Oils and Fats
- Food Production Side Streams
- Municipal Food Wastes

Totally more than one hundred feedstocks are included, being sufficient for most cases in Finland. New values can be added if corresponding analyses are available.

Table A1. Example of a biogas feestock database table.

Substrate	**dry matter**	**organic dm [%dm]**	**biogas yield [m^3/tn fresh matter]**	**CH_4 content [%]**	**N [kg / tn fresh]**	P_2O_5 [kg / tn fresh]	K_2O [kg / tn fresh]	digestion [kg/ tn fresh]	Na
Animal manures & slaughter wastes									
Animal carcasses	30.0 %	90%	243	**55**	22				
Blood	14.0 %	95%	76	70	21	2.5	2.5		
Breeding turkey litter	50.0 %	75%	270	62	16	20	16		
Chicken litter	40.0 %	75%	194	55	21	17	13	194	0.1
Chicken manure	60.5 %	75%	203	60	21			194	
Chicken meat	13.7 %	90%	96	55	10	3.1	0.8		
Cow milking slurry	8.5 %	85%	20	55	5				
Cow slurry manure	4.0 %	80%	18	58	4.5	2	6	23	0.1
Duck litter	30.0 %	75%	150	60	9	7	10		
Fattening chicken	50.4 %	75%	178	55	18	19	22		
Fattening turkey	45.0 %	75%	188	62	18	20	16		
Horse manure	31.7 %	75%	63	55	6			150	
Pig manure	22.5 %	83%	74	60	5				
Pig slurry manure	6.0 %	80%	19	60	5	3.5	3.5	23	
Poultry litter	15.0 %	75%	56	65	18				
Pullet manure (young chick	55.0 %	75%	204	55	18	19	22		
Rumen content	15.0 %	84%	61	55	5				
Sheep manure	30.0 %	80%	108	55	19				
Turkey manure	45.8 %	75%	188	65	25			194	

There may be local differences in the feedstocks, but for instance the grass in Southern Finland is rather homogenous, see Table A2.

Table A2. Biogas potential of grass in several Finnish cases.

Community	**ha**	ton TS	CH4, m³	MW	m³ CH4/ton TS
Riihimäki	18900	43085	12748630	15:09	296
Pukkila	14600	33374	9869553	12:03	296
Kouvola	16200	37150	10963791	13:07	295
Karkkila	11800	26854	7935196	9:09	295
Forssa	17400	41537	12110229	15:01	292
Siuntio	14200	32046	9508614	11:09	297
Joutseno	8700	19986	5894914	7:04	295
Artjärvi	13600	31143	9215565	11:05	296
Lahti	10400	23827	7035933	8:08	295
Rajamäki	18800	42607	12652003	15:08	297
				Average	295

Carbon Balance and Yield

When the feedstocks have been decided, the following step is to summarize the inputs and calculate the over-all (yearly) production based on estimated number of operating hours, see Table A3.

Table A3. **Example of calculation of yearly biogas production and other parameters.**

Operation	**95%**	8 322 h/a
Total feed		16 000 tn/a
Total DM		12 800 tn/a
Total oDM		11 738 tn/a
Biogas		8 551 924 m^3/a
Yield % of DM		80.2 %
CH^4		57.7 %
DM		80.0 %
oDM of DM		91.7 %

After this, the carbon balance can be calculated and the carbon yield estimated, see Table A4.

Table A4. **Calculation of carbon input and output.**

C content in oDM	50%						
		C in			C out		
DM	80.0 %		5 869 ton/a	43%	4 567 ton/a	Yield	77.8 %
AddOn carbon		Methane	58 in volume	9.23	6.92		
		CO^2	42 in volume	18.61	5.08 g/mol		
Biogas density		1.24 kg/m³		27.84	12.00 g/mol		
				Carbon	43.10% in weight		

If the yield seems to be too high compared to earlier experience, more conservative estimations should be used, or the residence time in the reactors increased (larger reactors).

Organic Load and Suspension Density

The *organic loading rate* (OLR) represents the amount of volatile solids of substrate per day. In mesophilic reactors, the average loading rate is usually in the range of 5.0 [kg/(m^3 day)]. This parameter is the key in reactor size calculation together with the *solids suspension density* (SSD), expressed as [kg d.s/m^3] or [% d.s.]. The SSD includes also the inorganic materials which are not settled at the bottom of the reactor, while the ORL takes into account only the carbon containing material. Based on the SSD, two main reactor types can be separated:

1. Wet reactors, which usually operate under 15 % d.s. or 150 [kg d.s/m^3].
2. Dry reactors, SSD over 15 % d.s.

Wet reactors require continuous or periodic mixing, while in the dry reactors, the liquid is circulated and the solid mass stays still or moves very slowly.

The *hydraulic retention (residence) time* is the average amount of time that liquid and soluble compounds stay in a reactor or a tank. It is calculated by dividing the volume of a reactor (e.g. m^3) by the influent flow rate (e.g. m^3/day). By using the values in Table A3 and an average SSD of 12 % d.s. with 21 days (three weeks) retention time, we get a reactor volume of

12 800 [ton/a] = 40 [ton d.s/day] (80 % dry matter)

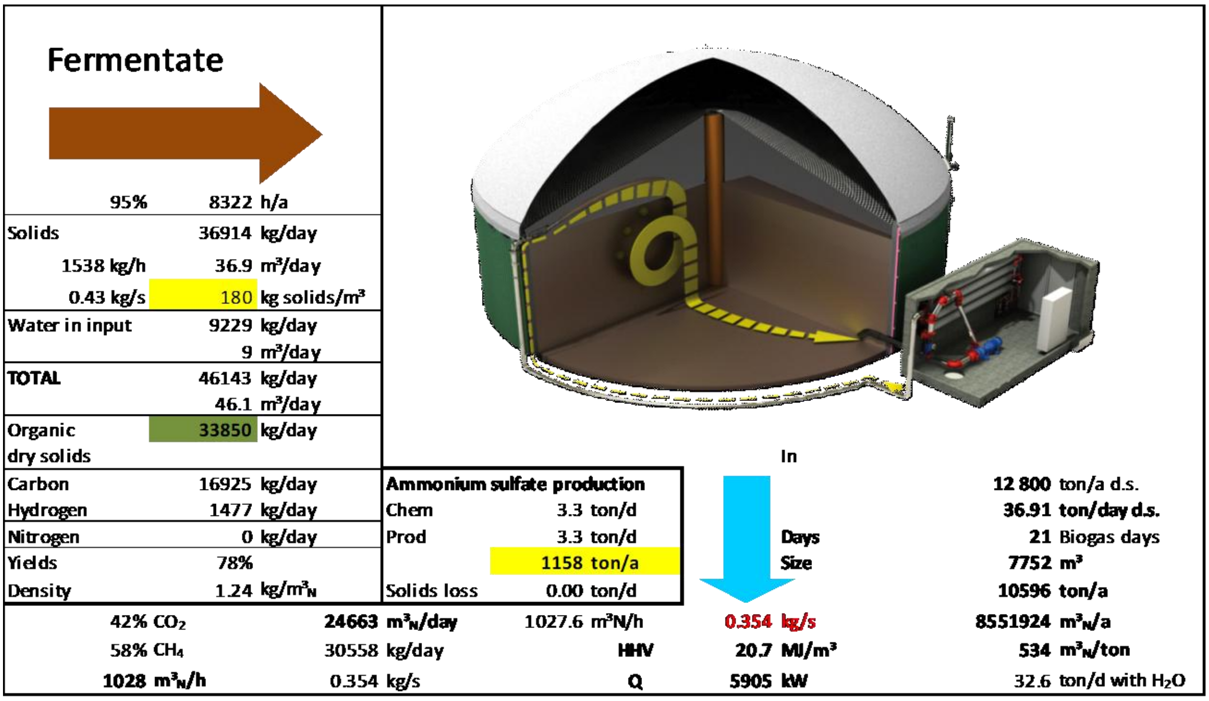
40 [ton d.s. /day] / 0.12 = [330 m^3 / day] {290 m^2 water and 40 m^3 d.s.}

21 days * 330 [m^3 / day] = **7 000 [m^3]**

34 [ton/day o.d.s] / 7 000 [m^3] = **4.8 [kg/(m^3 day)]** OK!

So this design would be suitable for a wet mesophilic process, if we assume that the density of the organic material is close to water density, which is usually the case.

At this stage, an overview of the plant and production figures can be generated, see Figure A1.


Fermentate

95%	8322	h/a
Solids	36914	kg/day
1538 kg/h	36.9	m^3/day
0.43 kg/s	180	kg solids/m^3
Water in input	9229	kg/day
	9	m^3/day
TOTAL	46143	kg/day
	46.1	m^3/day
Organic dry solids	33850	kg/day
Carbon	16925	kg/day
Hydrogen	1477	kg/day
Nitrogen	0	kg/day
Yields	78%	
Density	1.24	kg/m^3_N

Ammonium sulfate production		
Chem	3.3	ton/d
Prod	3.3	ton/d
	1158	ton/a
Solids loss	0.00	ton/d

In

	12 800	ton/a d.s.
	36.91	**ton/day d.s.**
Days	**21**	Biogas days
Size	**7752**	**m^3**
	10596	**ton/a**

42% CO_2	**24663**	**m^3_N/day**	1027.6 m^3N/h	0.354	kg/s	**8551924**	**m^3_N/a**
58% CH_4	30558	kg/day	**HHV**	**20.7**	**MJ/m^3**	**534**	**m^3_N/ton**
1028 m^3_N/h	0.354	kg/s	**Q**	**5905**	**kW**	32.6	ton/d with H_2O

Figure A1. Example calculation of a biogas plant feedstock input and production figures.

Biogas Purification

The produced biogas contains mainly methane (CH_4) and carbon dioxide (CO_2). The methane is the desired component, as the heating value (energy content) is high, 55 [MJ/kg]. However, there is an increasing interest to use the CO_2 as well. Thus, the emphasis is to:

A. Separate impurities, such as sulphur, see Figure A2.
B. Remove the CO_2, as it as the larger molecule is possible to filter or strip with liquid (absorb) from the biogas. If feasible, the CO_2 can be frozen to dry ice or sold a pressurized gas.
C. Purify (if needed) the methane and pressurise or even liquefy it to be transported and sold.

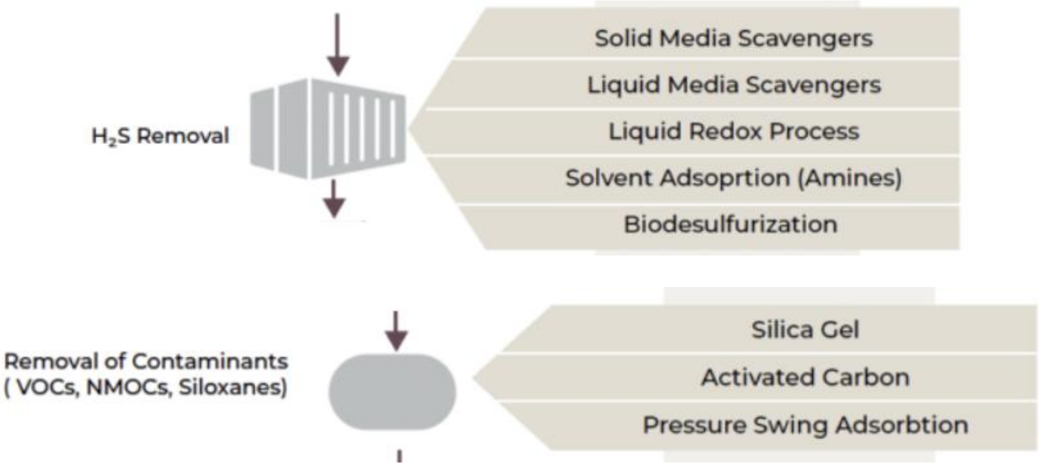


Figure A2. Example of H_2S and impurity removal from biogas.

There are three main paths for the purification (see also Figure A3):

I. Mechanical way (ultra filtration)
II. Chemical way (absorption or adsorption)
III. Cryogenic separation.

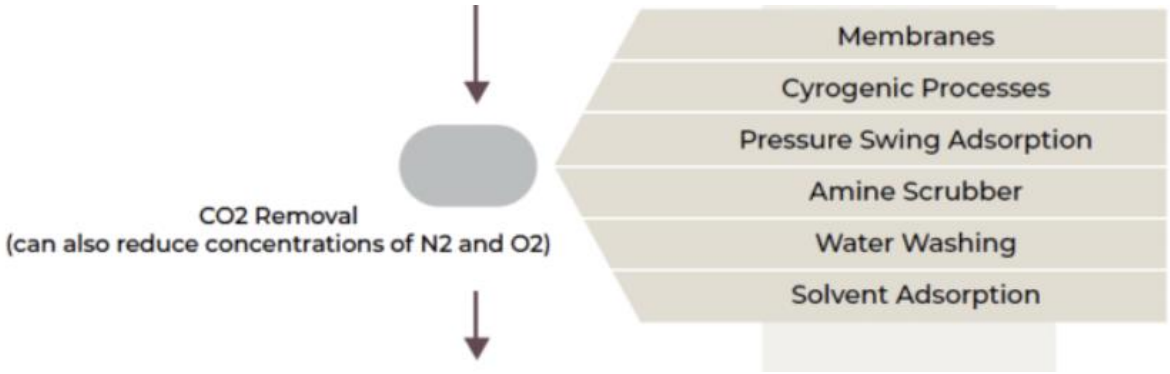


Figure 3. CO_2 removal from purified biogas.

Solid Residue (Digestate) Handling

The solids which are not converted to biogas (also known as *biogas residues* or *digestates*) are periodically removed from the reactor(s) and need to be treated before they can be stored or used for instance as fertilizers. Solids coming from wet reactors have high water content, and they usually need to be de-watered. The de-watering can be done by:

- Mechanical separators (filters, screw presses, centrifugal decanters, other systems)
- Thermal processes (dryers)
- Or combinations of these.

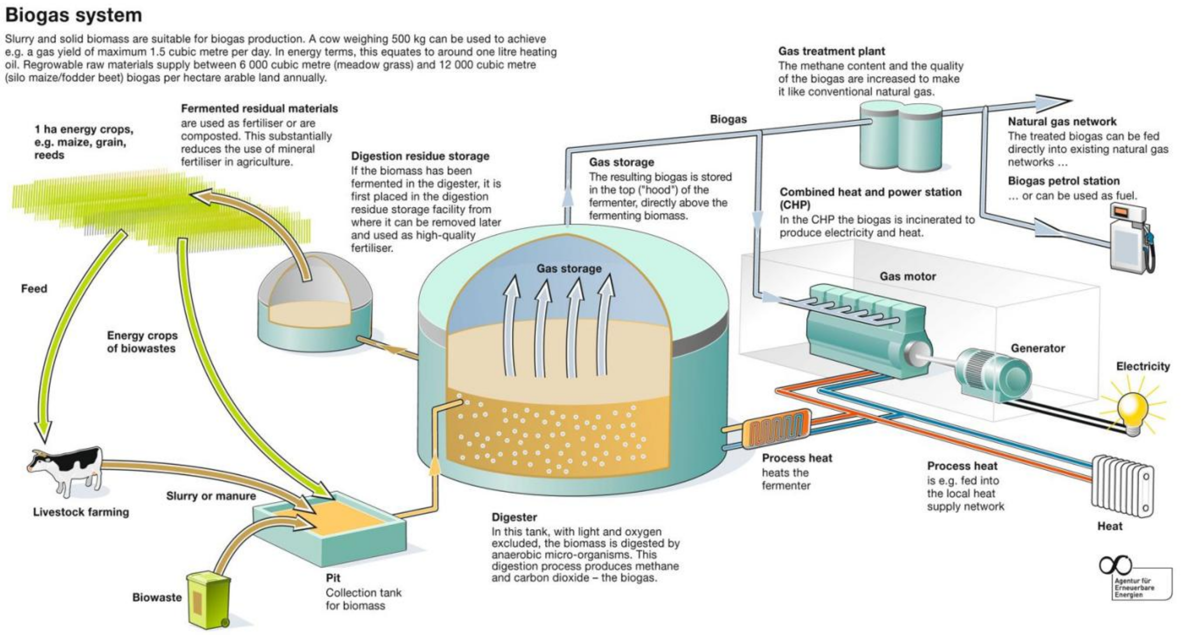
The inorganic nutrients in the feedstocks mainly end up in the digestate, but the fate of nitrogen can be much more complicated: nitrogen compounds may be found in the biogas, the liquid phase and in the solids. It may be feasible to evaporate ammonia from the digestate and handle it as a separate fraction and use the solids to create a potassium (K) and phosphorous (P) rich fraction.

Auxiliary Systems and Balance of the Plant (BoP)

In addition to the reactors, biogas purification and digestate handling, a biogas plant requires several additional components (see also Figure A4). *Balance of plant* (*BoP*) is a term used in engineering to refer to all the supporting components and auxiliary systems of a production plant needed to deliver the product not including the main units. In biogas production, these include:

- Feedstock receiving (scale for mass input) and storage systems
- Pre-treatment if necessary (sorting, crushing)
- Feed systems
- Heating systems (heat and power generation) and heat exchangers
- Mixers (can be included in the reactor structure)
- Liquid tanks
- Gas storages
- Blowers
- Pumps

- Electrical systems
- Automation
- Buildings and support structures.



Biogas system

Slurry and solid biomass are suitable for biogas production. A cow weighing 500 kg can be used to achieve e.g. a gas yield of maximum 1.5 cubic metre per day. In energy terms, this equates to around one litre heating oil. Regrowable raw materials supply between 6 000 cubic metre (meadow grass) and 12 000 cubic metre (silo maize/fodder beet) biogas per hectare arable land annually.

Fermented residual materials are used as fertiliser or are composted. This substantially reduces the use of mineral fertiliser in agriculture.

Digestion residue storage If the biomass has been fermented in the digester, it is first placed in the digestion residue storage facility from where it can be removed later and used as high-quality fertiliser.

Gas storage The resulting biogas is stored in the top ("hood") of the fermenter, directly above the fermenting biomass.

Gas treatment plant The methane content and the quality of the biogas are increased to make it like conventional natural gas.

Natural gas network The treated biogas can be fed directly into existing natural gas networks ...

Biogas petrol station ... or can be used as fuel.

Combined heat and power station (CHP) In the CHP the biogas is incinerated to produce electricity and heat.

Process heat heats the fermenter

Process heat is e.g. fed into the local heat supply network

Digester In this tank, with light and oxygen excluded, the biomass is digested by anaerobic micro-organisms. This digestion process produces methane and carbon dioxide – the biogas.

Pit Collection tank for biomass

Figure A4. Example of a biogas plant.

Examples

[Anaerobic Sequencing Batch Reactor ASBR Technology (youtube.com)]

Biogas Purification by Stripping (Absorption)

Absorption is a physical or chemical phenomenon or a process in which atoms, molecules or ions enter the liquid or solid (usually called adsorption) bulk phase of a material. The resulting compounds may be salts, azeotropes (an azeotrope is a constant-boiling mixture with a constant mole fraction composition of components. Azeotropes consist of two, three, or more components, and can be homogeneous or heterogeneous) or complex ions. Polar molecules such as water may also form polar electronegative bonds, in which the negative charge from the electrons is not evenly distributed in the molecule.

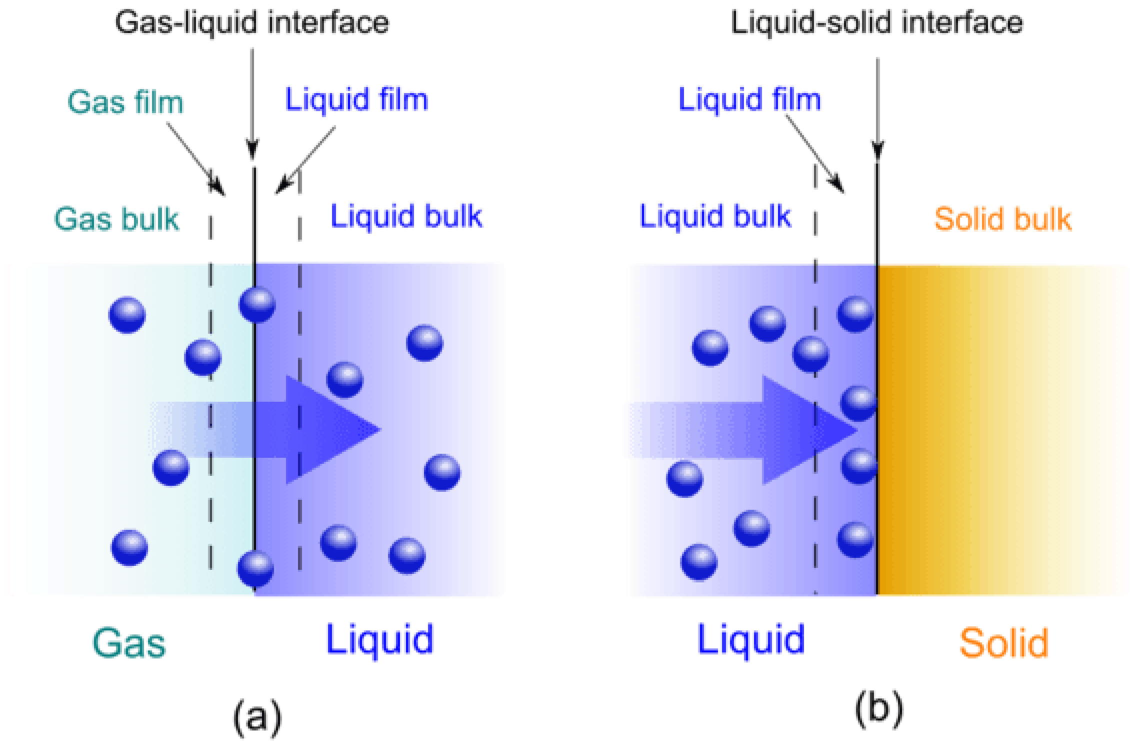


Figure B1. Absorption of gas into a liquid bulk and liquid to solid bulk.

Absorption is an efficient method of separating materials, especially in gaseous or liquid form. For instance, CO_2 and CH_4 in biogas can be separated by absorption by selecting an *absorbent* (liquid used for absorption) which is selective enough so that one of the components is absorbed while the other is not. For instance, solubility of CO_2 in water at 25 °C is about 1.5 [g/l], while for methane, the corresponding number is only 23 [mg/l], about 65 times lower. By selecting a more efficient absorbent, the solubility can be even higher. *Amines* are found to absorb CO_2 with high efficiency, and thus they are often used in biogas purification processes, while the use of water is usually done in high pressure absorption systems.

Amine Absrption

Amine is any member of a family of nitrogen-containing organic compounds that is derived, either in principle or in practice, from ammonia (NH_3). Naturally occurring amines include the alkaloids, which are present in certain plants; the catecholamine neurotransmitters (i.e., dopamine, epinephrine, and norepinephrine); and a local chemical mediator, histamine, that occurs in most animal tissues.

Ethanolamine (2-aminoethanol, monoethanolamine, ETA, or MEA) is a naturally occurring organic chemical compound with the formula $HOCH_2CH_2NH_2$ or C_2H_7NO. The molecule is bifunctional, containing both a primary amine and a primary alcohol. Ethanolamine is a colorless, viscous liquid with an odor reminiscent of ammonia.

Ethanolamine is commonly called monoethanolamine or MEA in order to be distinguished from diethanolamine (DEA) and triethanolamine (TEA). The ethanolamines comprise a group of amino alcohols. A class of antihistamines is identified as ethanolamines, which includes carbinoxamine, clemastine, dimenhydrinate, chlorphenoxamine, diphenhydramine and doxylamine.

The solubility of CO_2 in for example MEA is high compared to for instance water. The molar mass of MEA is 60.1 [g/mol], while the molar mass of CO_2 is 44 [g/mol]. This means that when the solubility of CO_2 in a 30 % mixture of MEA and water has been measured to be about 0.6 [mol/mol], meaning that the maximum amount of CO_2 per one litre of solution is 130 [g]. When the temperature is increased, the solubility decreases. This means that the MEA/water solution can be regenerated, i.e. the CO_2 can be “boiled out” due to *desorption*. The *system efficiency* describes the rate of absorption/desorption, meaning that while some CO_2 may still be present in the MEA/water solution after the desorption, the liquid can still absorb a significant amount of CO_2.

The system efficiency can be shown in unit [g/l], which in turn helps to determine the required liquid flow in the absorber compared to the biogas flow rate. For instance, if we design a purification system for 10 GWh biomethane production, we need about 260 kg/h biogas with 55 % CH_4 content. The mass flow rate of CO_2 is about 180 [kg/h], corresponding to 50 [g/s]. If we assume 75 % system efficiency, we need only 0.5 [l/s] absorbent.

When we have the estimated liquid flow rate, the next task is to determine the cross-section of the reactor. When the gas flow rate is [0.06 m^3/s] and we have a packed bed reactor, by estimating the free cross-section we can calculate the gas velocity in the reactor. If we have a reactor with 1 [m] inside diameter and the free cross-section is estimated to be 30 % (a heavily packed reactor), we get

$$(0.06\ m^3/s\ )\ /\ \{(1.0\ m)^2 * \pi\ /\ 4 * 30\,\%\} = 0.25\ [m/s].$$

By selecting a 10[m] high cylinder, we get 40 [s] residence time, which should be long enough to achieve the desired degree of absorption. External cooling of the liquid could improve the efficiency.

The main challenge is to select the best reactor design, a packing type, and design the liquid nozzle so that the liquid is spread evenly on the packing surfaces.

A (randomly) *packed bed reactor* (see Figure B2) is a tube which is filled with packing material called *rings*, see Figure B3 for reference. The idea is to get a large reaction surface without increasing the pressure drop too much: a compromise between absorption efficiency and energy consumption. The absorber works best as type (b), where the gas flows upwards and the absorbent flows down through the packing.

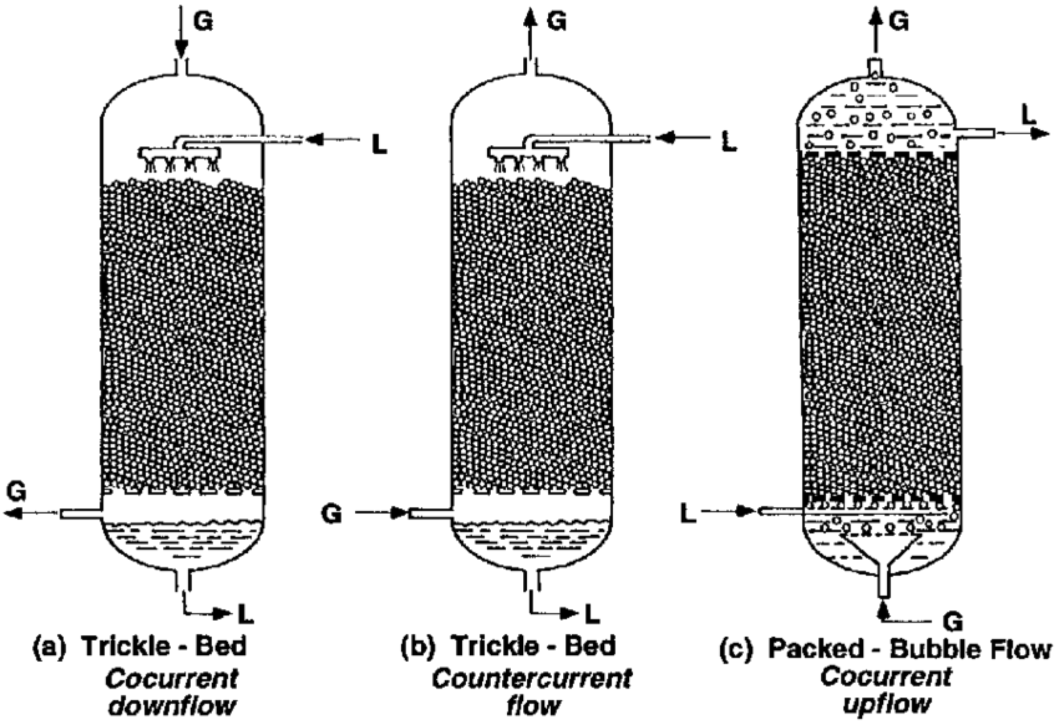


Figure B2. Different types of vertical reactors with increased reaction surface.

Figure B3. Examples of packed bed rings (packing materials).

Absorption System

In addition to the absorber, a desorber is needed. The same principles but reverted can be used: the idea is to release as much CO_2 as possible without using too much energy or compromising the mechanical structures. The desorber is also a randomly packed reactor, but as the residence time is determined by the retention time of the liquid, a smaller unit should suffice. The external energy needed for the heating and desorption can be produced by burning some of the raw biogas, but as the biomethane is the most valuable product, its quantity should be maximized. Thus, it may be more feasible to use another energy source: if there is district heating or residual heat from another process available, such heat should be the preferred energy source.

As the desorption takes place in an elevated temperature, it makes sense to use this heat to pre-heat the liquid coming from the absorber. This in turn helps to cool down the liquid, thus increasing the absorption efficiency. Additional cooling might be a feasible investment, as there is always a gradation (loss of temperature) in a heat exchanger. Plate-type heat exchangers are inexpensive and efficient units with small spatial need.

A blower for the raw biogas and another for the biomethane are usually needed. These are special ATEX-rated units (explosion risk area). Pumps for the liquids do not have to be otherwise special, except that the chemicals pumped may contain impurities such as sulphur, so the materials should be selected accordingly. Traditional centrifucal pumps are efficient and robust solution for all the pumping needed.

Table B1 shows the proposed minimal equipment needed with some optinal components, and such a system is illustrated in Figure B4. A preliminary flow diagram is shown in Figure B5 and a PID for a more advanced system is shown in Figure B6.

Table 1. Proposed list of equipment with some parameters (initial).

COMPONENT	PURPOSE AND SIZE
Gas blower	Gas flow into stripper, 1 000 m^3/h
Stripper	Dilution of CO_2 into amine, H 10 m, D 0.5 m
Amine pump	Circulation of amine, 10 m^3/h
Heat exchanger	Pre-heating of CO_2 rich amine, 500 kW
Regenerator	Evaporation of CO_2, H 5 m, D 0.5 m
Heater	Heating of regenerator, 100 kW
Cooler	Cooling of regenerated amine, 100 kW
CH_4 compressor	Pressurization of methane, 10 m^3/h, 250 bar(g) OPTION
Methane tank	Storing of methane, 50 m^3, 300 bar(g) OPTION
CO_2 compressor	Pressurization of CO_2, 20 m^3/h, 100 bar(g) OPTION
CO_2 tank	Storing of CO_2, 20 m^3, 120 bar(g) OPTION

COMPONENT
A Gas blower
B Stripper
C Amine pump
D Heat exchanger
E Regenerator
F Heater
G Cooler

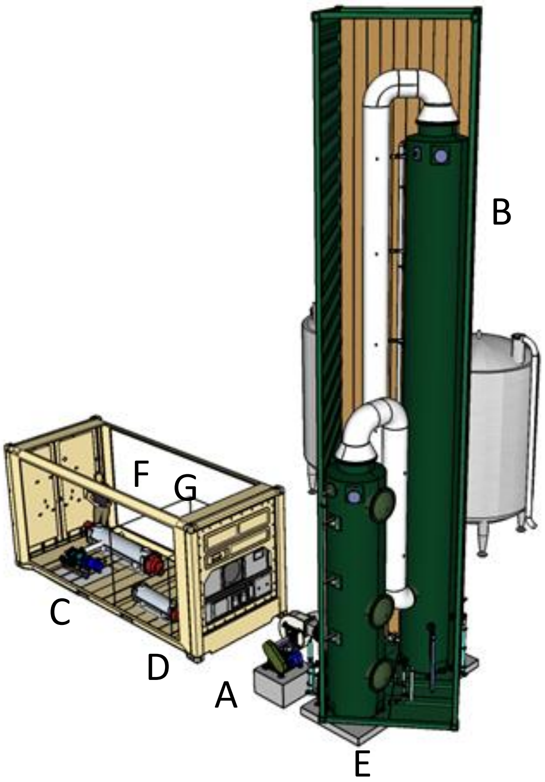


Figure B4. Illustration of an amine stripper system for biogas purification.

If the main equipment is pre-build into standard transport (sea) containers, the assembly is quick and easy. Electrical systems and automation can be placed in a separate space inside the smaller container.

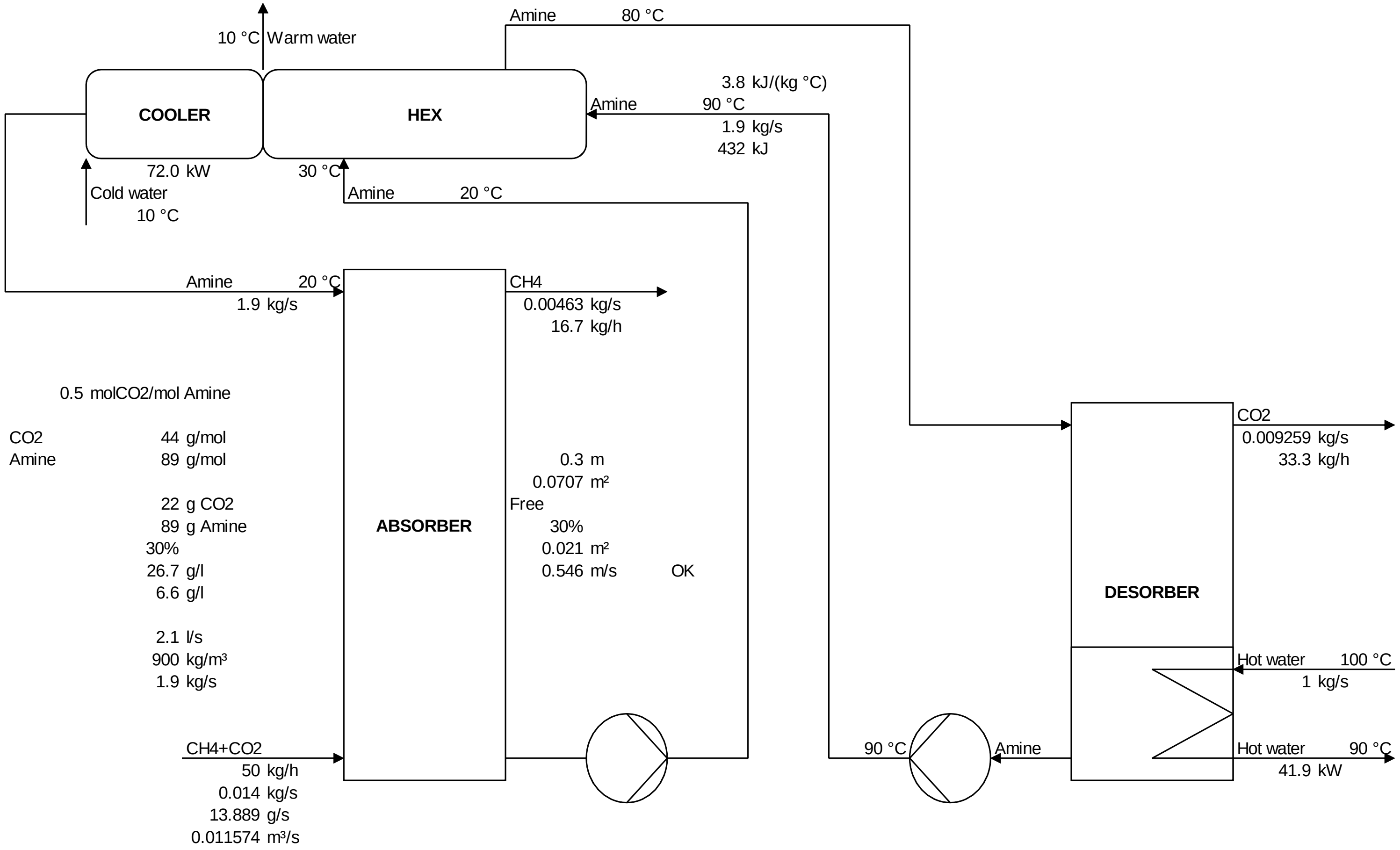


Figure B5. Example of a flow diagram with some initial calculations.

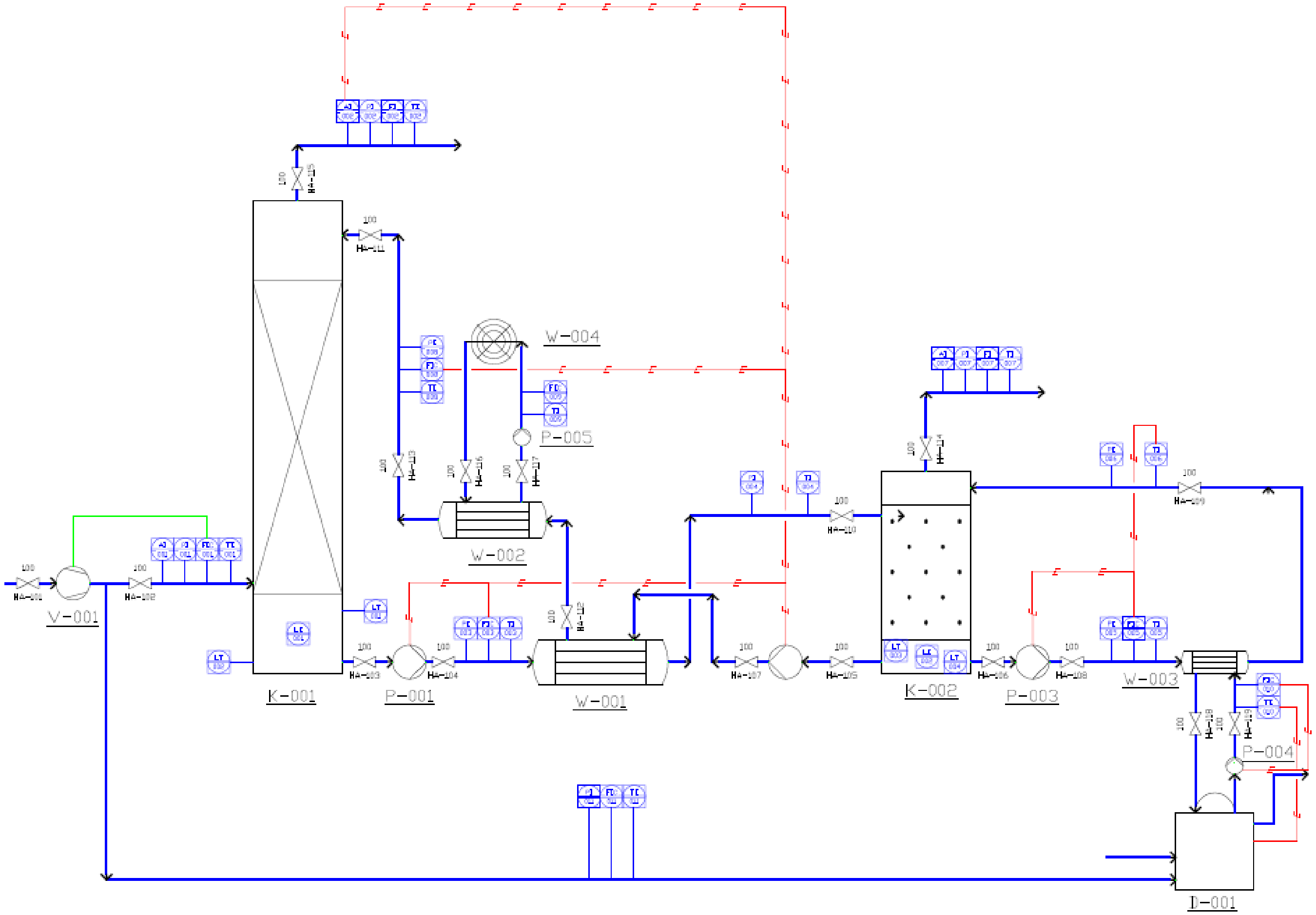


Figure B6. A preliminary PID for an amine absorption system for biogas purification.

Operation Description

The purpose of the *amine stripper* is to purify biogas so that the produced biomethane has more than 98 % methane (CH_4) with a capacity of more than 10 GWh per year. The unit is based on stripping with amine solution and chemical recovery by heating of the liquid. The released CO_2 can be purged into the atmosphere, or when feasible, collected and re-used. The biomethane product is pressurized and transported to use or further treatment (liquefaction to LBG).

Main Functions

There are six interconnected main functions:

1. Absorption
2. Desorption
3. Heat recovery
4. Energy generation
5. Cooling
6. Chemical mixing and feeding.

The absorber K-001 is a vertical column reactor with randomly packed bed. The raw biogas enters from the bottom of the reactor and flows upwards through the packing, while the absorbent is sprayed at the top of the reactor and flows downwards into a collecting tank built as a part of the structure. The role of the packing is to provide large amount of surface needed for the absorption. The blower V-001 is used to provide pressure to compensate the pressure drop. The biomethane product leaves the absorber top and is collected into a storage tank.

The liquid is transported from the absorber by pump P-001 through a heat exchanger W-001, in which it is pre-heated by the liquid returning from the desorber K-002. The desorber is similar to the absorber but shorter. External heat is provided by using the boiler D-001 with a heat exchanger W-003, into which the hot water is pumped from the boiler by pump P-004. The pump P-003 provides liquid flow to and from the desorber through W-003. The CO_2 absorbed into the liquid is released in gaseous form and purged into the atmosphere from the top of the desorber, or when feasible, collected and re-used. Pump P-002 returns the CO_2-free liquid through the heat exchanger W-001 and cooler W-002 into the absorber.

The heating system D-001 has a burner, boiler and auxiliaries.

The cooling system consists of the cooler W-004 and pump P-005, which provides flow through the heat exchanger W-002.

A separate system for mixing and feeding is included into the system.

Automation and Controls

The measurements are connected to the local I/O card inside a cabinet at the equipment container. A local PLC with a touch-screen display is located on the door of the cabinet. A separate computer is used for remote control and data-logging. The main controls are:

A. Biomethane quality control. The biogas flow and the absorbent flow are adjusted by a cascade control so that if the CH_4 level in the product drops below 98 %, at first the absorbent flow rate is increased by adjusting pump P-002. If this is not sufficient, the biogas flow rate is reduced by adjusting the blower V-001.
B. The flow of the liquid from the absorber to the desorber (P-001) is connected to the flow of liquid returning from the desorber, so that the Pump P-002 provides the same flow rate as P-001. This is adjusted by the two level measurements, one for the absorber and the other for the desorber. If the levels start to decrease, more amine solution is added into the system.
C. The desorber heating is firstly adjusted by the pump P-003. If the temperature is not increasing sufficiently, the pump P-004 provides more flow into the heat exchanger W-003. If this is still not enough, the boiler water temperature starts to increase until a desired desorber temperature is reached.
D. The absorbent temperature is adjusted by changing the temperature after the cooler W-002 by controlling the pump P-005.

Special gas quality measurements for the biogas entering the system, produced biomethane and CO_2 are included. The absorbent composition can also be followed.

Flows, pressures and temperatures are followed and logged. There are two level measurements and four level switches for the absorbent levels, one set in the adsorber and one for the desorber. These are also followed and logged. Pump and blower motors are connected to frequency converter which serve as flow control devices. The boiler has its own safety systems and interlocks.

Sequences

1. Liquid filling
    - Check that valves HA-102, HA-103, HA-104, HA-105, HA-119 and HA-120 are open
    - Start pump P-006
    - Run until level LT-001 or LT-003 becomes active
2. Main operation, liquid circulation
    - Check that valves HA-102, HA-103, HA-104, HA-105, HA-106, HA-107, HA-108, HA-109, HA-110, HA-111, HA-112 and HA-113 are open
    - Start pump P-001
    - Start pump P-002
    - Follow levels LI-001 and LI-002, adjust pump speeds so that both levels stay constant.
3. Main operation, heating and cooling

- Check that valves HA-115 and HA-116 are open
- Start pump P-005
- Start cooler W-001
- Check that valves HA-117 and HA-118 are open
- Start pump P-004
- Start boiler D-001

4. Main operation, stripping
    - Check that valves HA-100, HA-101, HA-113 and HA-114 are open
    - Start blower V-001, increase rpm slowly to pre-set running point
    - Follow gas composition and activate the liquid flow controller
    - Reduce gas flow if CH_4 content drops below 98 %.

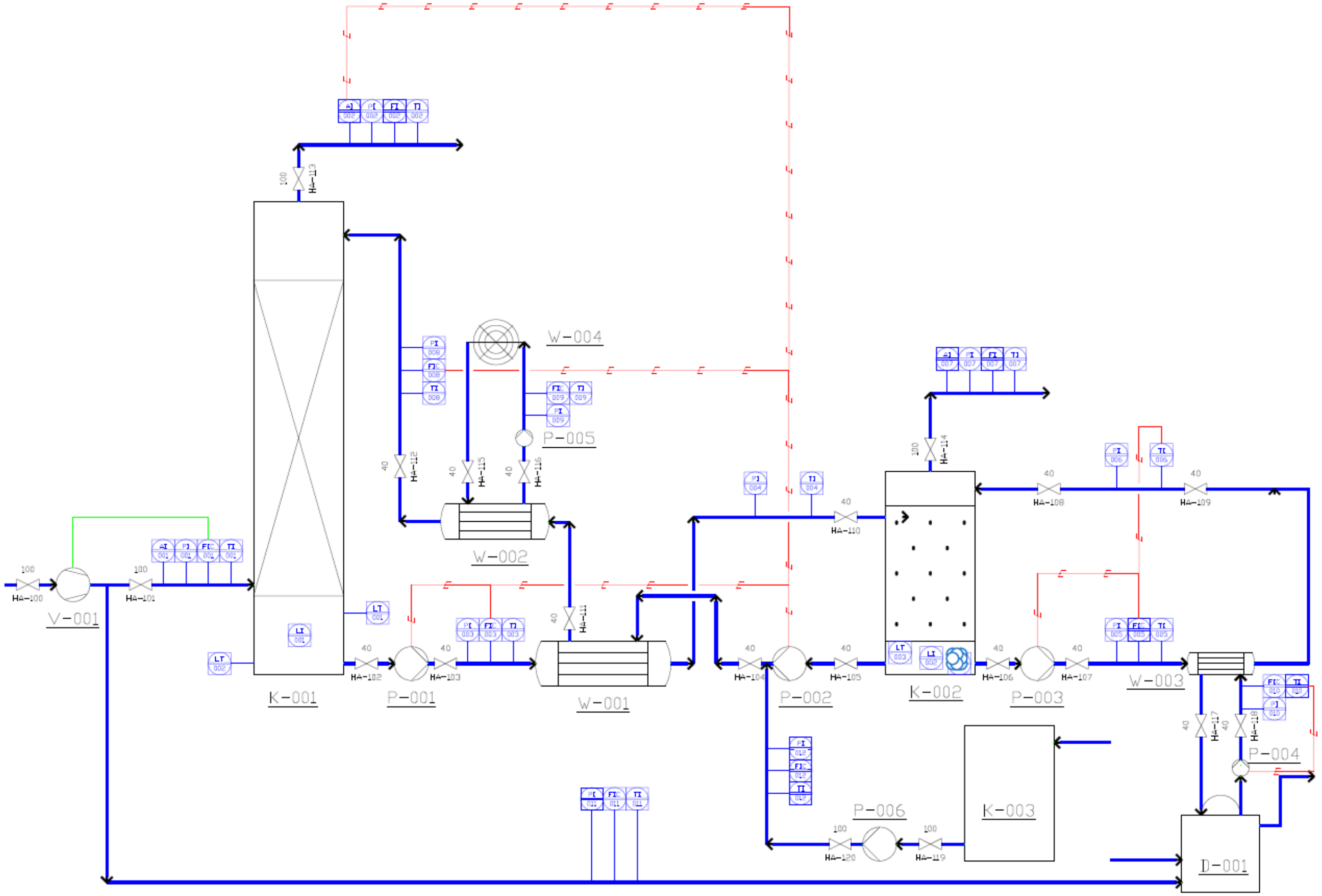


Figure 1. Stripper PID

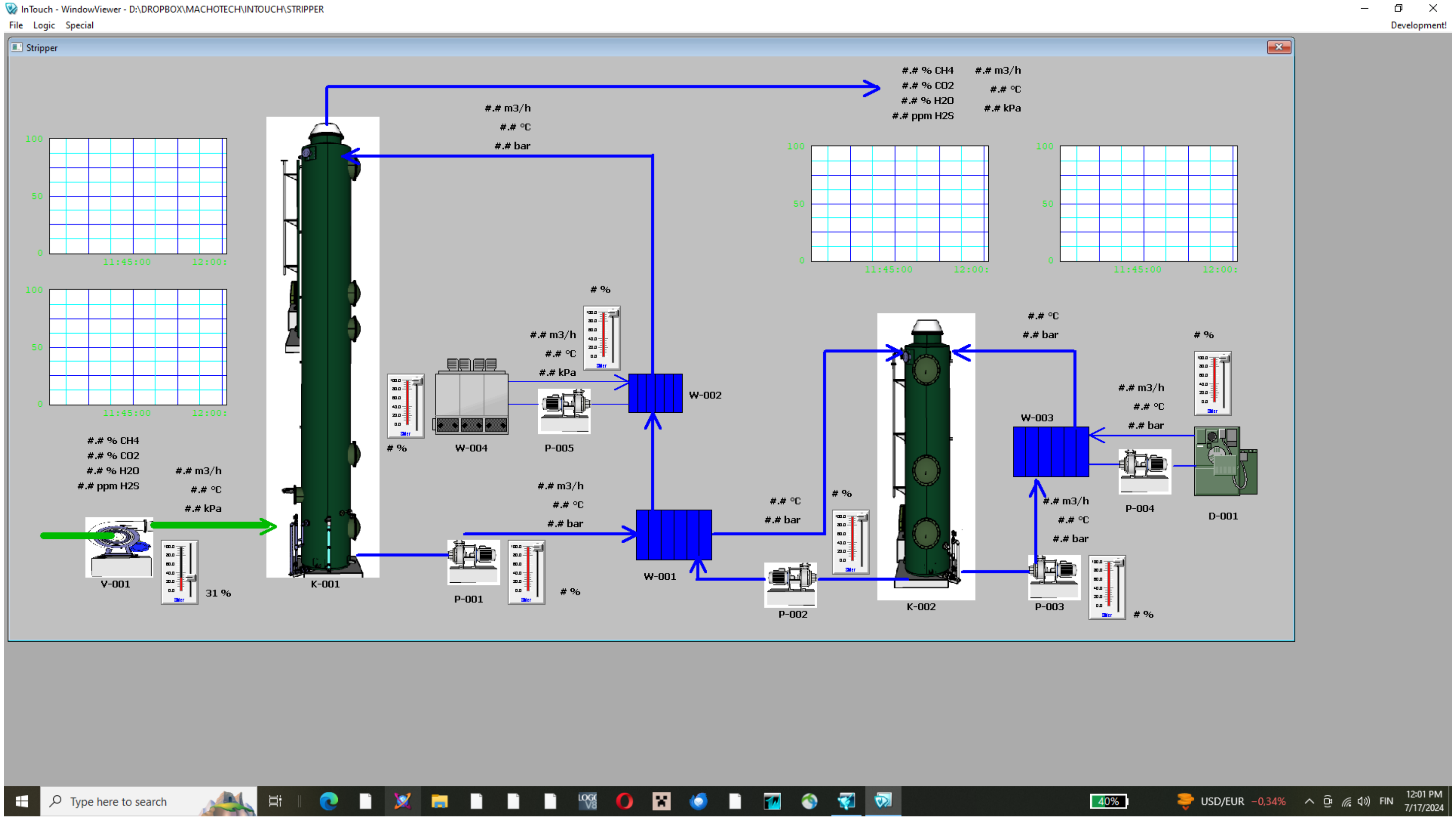


Figure 2. Example of an operating screen.

Background

As a vital part of the study on absorption of CO_2 by amines is to verify how this process could be modelled. There are several articles available, some of the public and some of the behind a pay-wall. How ever, by using the basic theories and some justified assumptions, a simplified model for the absorber can be generated.

Absorption and Mass Transfer

The general equation for absorption can be written in form:

$$q \qquad \frac{\qquad}{\qquad} \tag{D1}$$

Where q_D rate of diffusion, [mol/s]
D_f diffusion coefficient, [m^2/s] or [cm^2/s]
A area available for diffusion, [m^2] or [m^2/m^3]
ΔC concentration gradient, [mol/m^3]
ΔX diffusion distance, [m].

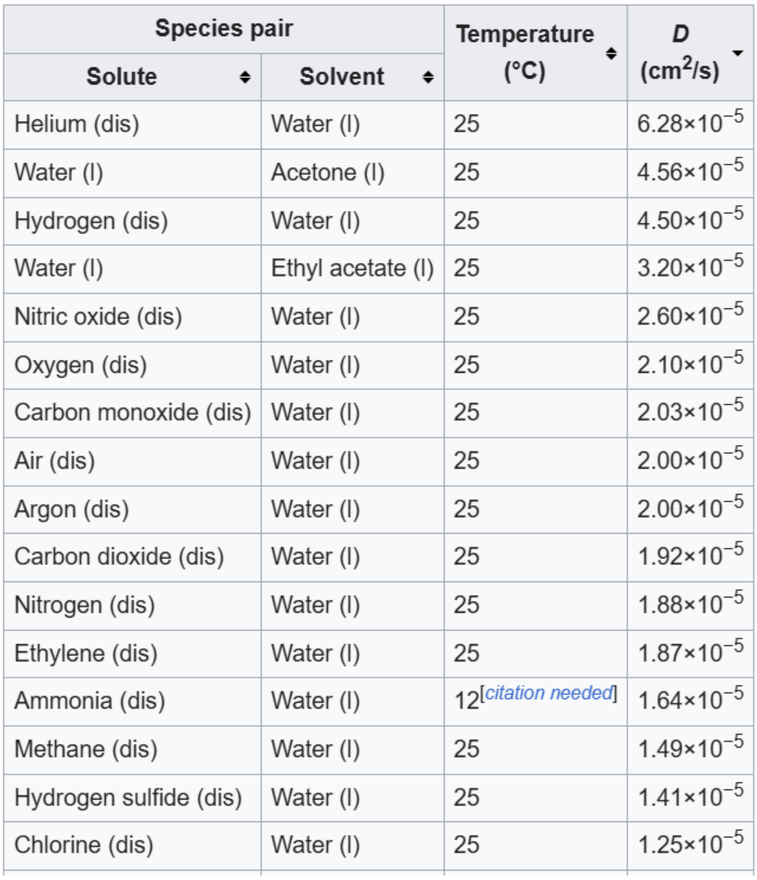
As the target is to capture as much CO_2 as possible, the parameters to be optimized include all of the right side variables:

- The diffusion coefficient is usually described as the proportionality constant between the molar flux due to molecular diffusion and the negative value of the gradient in the concentration of the species. Several methods for determining the coefficient theoretically have been found, but the most reliable values can be found by conducting experiments, see for instance Table D1.

- The area available for diffusion is a very important parameter, and in itself explains why packed beds are usually selected for reactor types in absorption. Table D2 shows some packing materials with their characteristics. The values for absorption area vary significantly depending on the selected material.

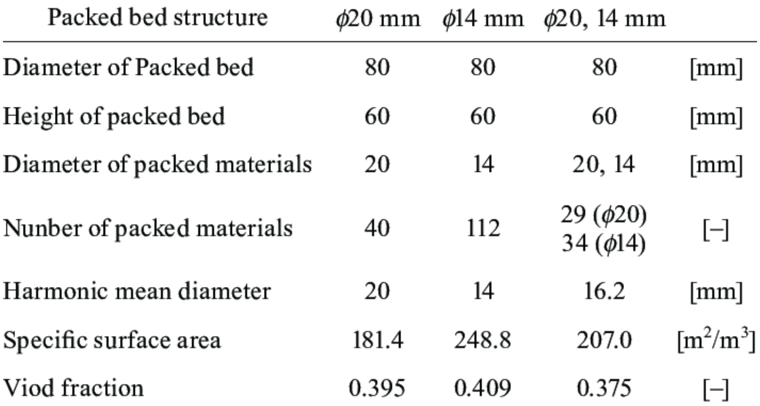
- The concentration gradient determines the driving force available for diffusion, and the diffusion distance indicates the rate and degree of maximal diffusion.

Table D1. Examples of diffusion coefficients.



Species pair		Temperature (°C)	*D* (cm²/s)
Solute	Solvent		
Helium (dis)	Water (l)	25	6.28×10^{-5}
Water (l)	Acetone (l)	25	4.56×10^{-5}
Hydrogen (dis)	Water (l)	25	4.50×10^{-5}
Water (l)	Ethyl acetate (l)	25	3.20×10^{-5}
Nitric oxide (dis)	Water (l)	25	2.60×10^{-5}
Oxygen (dis)	Water (l)	25	2.10×10^{-5}
Carbon monoxide (dis)	Water (l)	25	2.03×10^{-5}
Air (dis)	Water (l)	25	2.00×10^{-5}
Argon (dis)	Water (l)	25	2.00×10^{-5}
Carbon dioxide (dis)	Water (l)	25	1.92×10^{-5}
Nitrogen (dis)	Water (l)	25	1.88×10^{-5}
Ethylene (dis)	Water (l)	25	1.87×10^{-5}
Ammonia (dis)	Water (l)	12[citation needed]	1.64×10^{-5}
Methane (dis)	Water (l)	25	1.49×10^{-5}
Hydrogen sulfide (dis)	Water (l)	25	1.41×10^{-5}
Chlorine (dis)	Water (l)	25	1.25×10^{-5}

Table D2. Comparison of different packing materials.



Packed bed structure	ϕ20 mm	ϕ14 mm	ϕ20, 14 mm	
Diameter of Packed bed	80	80	80	[mm]
Height of packed bed	60	60	60	[mm]
Diameter of packed materials	20	14	20, 14	[mm]
Nunber of packed materials	40	112	29 (ϕ20) 34 (ϕ14)	[–]
Harmonic mean diameter	20	14	16.2	[mm]
Specific surface area	181.4	248.8	207.0	[m²/m³]
Viod fraction	0.395	0.409	0.375	[–]

Porosity (Void) and Pressure Drop

The porosity or void (ε) tells how much "empty space" the reactor has. This space is naturally occupied with the gas and liquid, and the pressure drop over the absorber greatly depends on this void space. Figure D1 illustrates the different zones in a randomly packed reactor and the resulting dependence of fraction coefficient on packing and the Reynolds number (mainly velocity).

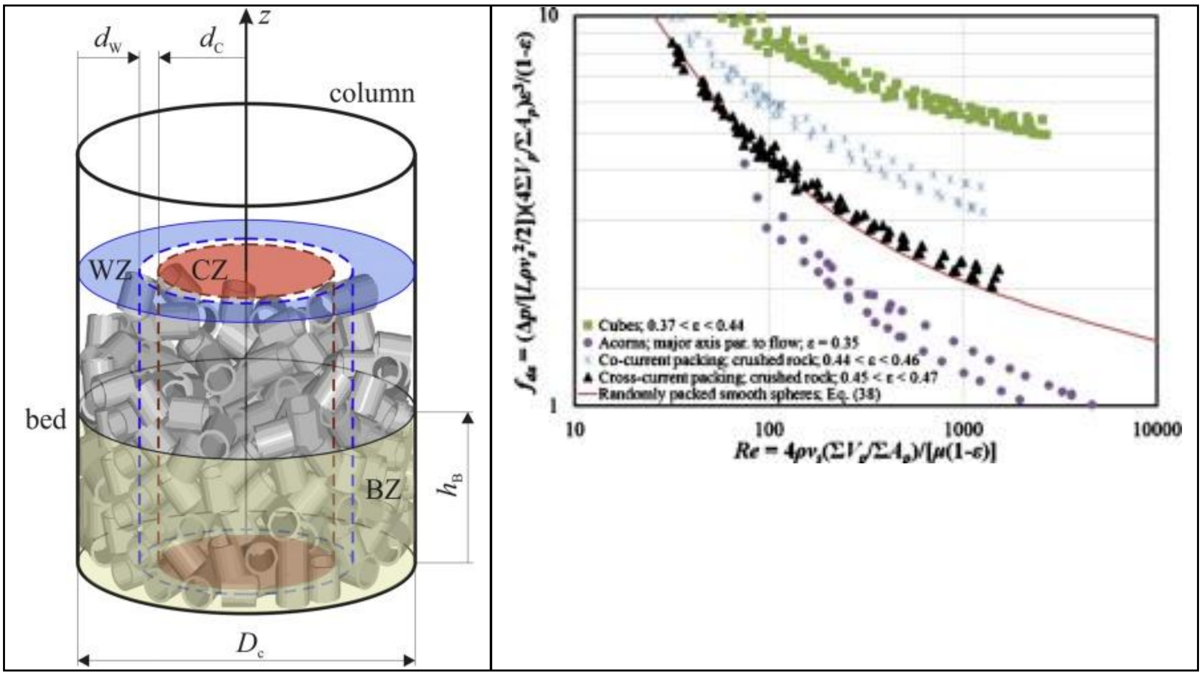


Figure D1. A randomly packed reactor and some pressure drop coefficients.

The general pressure drop equation is usually written in form

– —— (D2)

Where		
	Δp	pressure drop, [Pa]
	f	friction coefficient, [-]
	L	length of reactor, [m]
	d	hydraulic diameter, [m^2]
	ρ	fluid density, [kg/m^3]
	w	fluid velocity, [m/s].

The main unknown is the friction coefficient, which can be estimated based on the Reynolds number. Several systems have been studied, see for instance Table D3. The Reynolds number is often presented as:

—— (D3)

Where
Re Reynolds number, [-]
l characteristic length, [m]
ρ fluid viscosity, [Pa s].

The hydraulic diameter can be used to replace the characteristic length.

Table D3. Examples of correlations for friction factor in packed bed.

Eq. No	Author and year	Friction factor (*f*)	Re_p range	Shape and types
5	Ergun (1952)	$f = \frac{150}{Re_p} + 1.75$	Re_p < 1000	Spheres
6	Carman (1937)	$f = \frac{180}{Re_p} + \frac{2.87}{Re_p^{0.1}}$	0.1 to 60,000	Spheres
7	Hicks (1970)	$f = \frac{6.8}{Re_p^{0.2}}$	300 to 60,000	Spherical
8	Wilcox and Krier (1983)	$f = \frac{150}{Re_p} + \frac{3.89}{Re_p^{0.13}}$	1000 to 100,000	Spherical
9	Brauer (1971)	$f = \frac{160}{Re_p} + \frac{3.1}{Re_p^{0.1}}$	0.01 to 40,000	Spheres
10	Erdim et al. (2015)	$f = \frac{160}{Re_p} + \frac{2.81}{Re_p^{0.096}}$	$0.37 < \varepsilon < 0.47$, $4 < L/D_P < 34$, and $2 < Re_p < 3600$	Spheres of 9 different sizes
11	K. Allen (2013)	$f = \frac{129}{(2/3)Re_p} + \frac{3.27}{((2/3)Re_p)^{0.12}}$		Spheres
12	Handley and Heggs (1968)	$f = \frac{368}{Re_p} + 1.24$	Re_p > 200	Spherical
13	Regar et al. (2023)	$f = \frac{160}{Re_p} + \frac{3f(\varepsilon)}{Re_p^{0.1}}$	$625 < Re_p < 10{,}000$	Spheres
		$f(\varepsilon) = 253.9\varepsilon^4 - 499.3\varepsilon^3 + 364.7\varepsilon^2 - 115.6\varepsilon + 14.21$		

Calculations and Assumptions

The reactor can be calculated as a system with repeating base processes by dividing the height into several individual "calculation cells" where diffusion takes place independently of the other cells, but the conditions at the boundaries determine the over-all results. For instance, the VAMK project reactor has an 8 m high packed bed section, which can be divided into eight 1 m high subsections.

When the gas enters the system, it has a certain pre-determined composition: impurities such as sulphur components have been removed and the gas is dry. In this case, the gas contains 55 % CH_4 and 45 % CO_2 in molar (volume) basis. The gas meets the amine solution which has already absorbed significant amount of CO_2, thus the available concentration gradient has been reduced. To get the composition of the amine, the whole system needs to be calculated, leading to an iterative calculation process.

There are several interlinked tables, which are used to calculated the state of the gas and liquid at the cell boundaries, see Tables D4 to D6. Figure D2 shows the calculated result, i.e. the CH_4 and CO_2 contents in the gas phase. Table D7 shows the calculated pressure drop.

Table D4. State of the biogas at different cells.

H, m	qm, kg/s	ρ, kg/m^3	V, m^3/s	M, g/mol	N, mol
8	0.022	0.79	0.03	16.1	49.3
7	0.023	0.80	0.03	16.2	49.3
6	0.023	0.81	0.03	16.5	49.3
5	0.025	0.85	0.03	17.2	49.3
4	0.028	0.91	0.03	18.5	49.3
3	0.034	1.02	0.03	20.7	49.3
2	0.044	1.15	0.04	23.4	49.3
1	0.057	1.29	0.04	26.1	49.3
0	0.072	1.41	0.05	28.6	49.3

Table D5. Composition and relevant parameters for the biogas at different cells.

Gas										
CO_2 kg/s	CH_4 kg/s	CO_2 mol/s	CH_4 mol/s	CO_2 mol-%	CO_2 mol/m^3	CH_4 mol-%	CH_4 mol/m^3	ΔC mol/m^3	ΔCO_2 kg/s	ΣCO_2 kg/s
0.0002	0.0221	0.0035	1.381	0%	0.1	100%	27.1	0.1	0.0001	0.0001
0.0004	0.0221	0.0095	1.381	1%	0.3	99%	27.1	0.3	0.0003	0.0004
0.0011	0.0221	0.0246	1.381	2%	0.9	98%	27.1	0.8	0.0007	0.0010
0.0027	0.0221	0.0606	1.381	4%	2.1	96%	27.1	1.8	0.0016	0.0026
0.0061	0.0221	0.1376	1.381	9%	4.5	91%	27.1	3.9	0.0034	0.0060
0.0122	0.0221	0.2780	1.381	17%	8.3	83%	27.1	7.1	0.0062	0.0122
0.0217	0.0221	0.4942	1.381	26%	13.0	74%	27.1	11.0	0.0095	0.0217
0.0344	0.0221	0.7829	1.381	36%	17.8	64%	27.1	14.7	0.0127	0.0344
0.0497	0.0221	1.1295	1.381	45%	22.2	55%	27.1	17.7	0.0153	0.0496

Table D6. State of liquid at different cells.

Liquid						
qm, kg/s	ρ, kg/m^3	M, g/mol	N, mol	60% H_2O mol/m^3	0% CO_2 mol/m^3	40% MEA mol/m^3
0.369	5.9	27.8	44.3	34.2	0.0	10.1
0.369	5.9	27.8	44.3	34.2	0.0	10.1
0.370	5.9	27.8	44.4	34.2	0.1	10.1
0.372	5.9	27.9	44.5	34.2	0.2	10.1
0.375	6.0	28.0	44.8	34.2	0.5	10.1
0.381	6.1	28.2	45.4	34.2	1.1	10.1
0.391	6.3	28.5	46.2	34.2	2.0	10.1
0.404	6.5	28.9	47.4	34.2	3.1	10.1
0.419	6.7	29.3	48.8	34.2	4.5	10.1

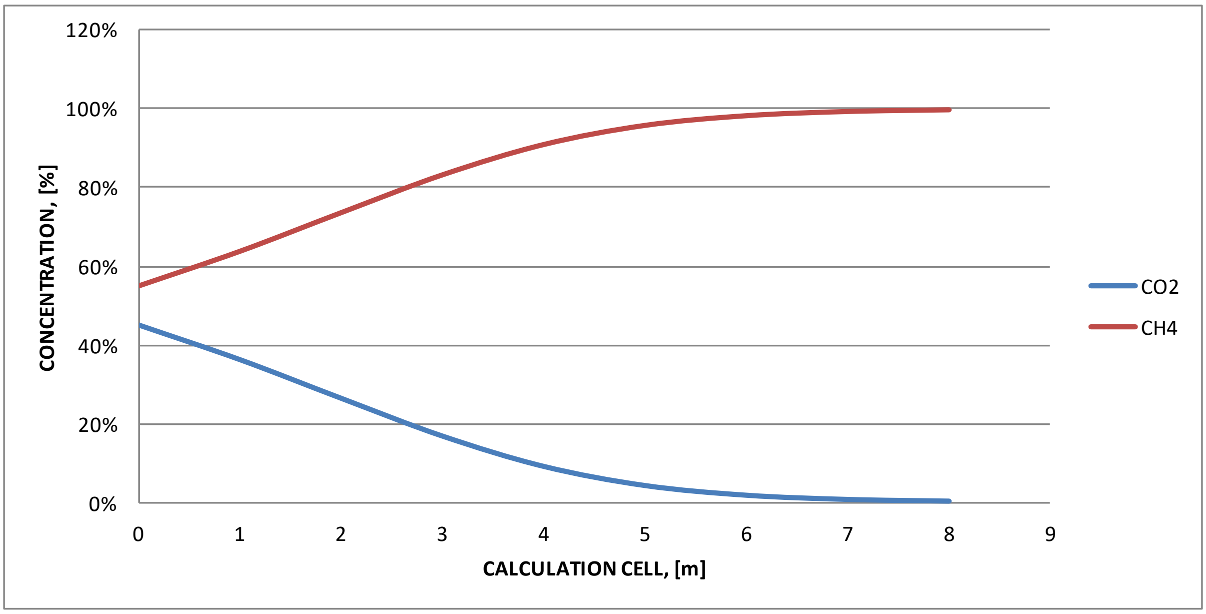


Figure D2. Calculated gas composition in the absorber, x-axis is meters from the bottom of the packed reactor.

Table D7. Estimated pressure drop.

D	1	m
A	0.79	m^3
w	0.0784	m/s
ε	30%	-
D'	0.300	
w'	**0.261**	**m/s**
μ	1.57E-05	m^2/s
Re	**1195**	-
f	1.88	-
Δp	2.0	Pa

Conclusions and Recommendations

The brief study on the modelling of absorber column shows that an initial model can be generated with Microsoft Excel. Although the diffusion coefficient was based on a value taken from literature, the result corresponds to data from similar absorbers. By using this model, the effect of flows, amine concentration and role of the packaging can be studied before any laboratory or pilot scale test are performed. This saves time and effort, because the most extreme combinations can be neglected.

The next steps are in improving the model and finding best correlations for absorption coefficient, especially dependence on the amine mixture.

Introduction

In addition to the main equipment (reactors, heat exchangers, boiler and cooler) the system needs pumps for the absorbent, blower(s) for the gases, valves and measuring instruments for safe operation.

Pumps and Fluid Transfer

The role of a pump is to generate a pressure difference, which forces the liquid to move from one place to another via piping. There are several possible pump types which would perform the task, but some pumps are more suitable than others (see also Figure E1):

- **Centrifugal Pumps**: These pumps use an impeller to create centrifugal force, which moves fluid through the pump. They are commonly used for water, chemicals, and other liquids.
- Positive Displacement Pumps: These pumps use mechanical action to move fluid through the pump. They are commonly used for viscous fluids such as oil and food products.
- Submersible Pumps: These pumps are designed to be fully submerged in fluid, typically water. They are commonly used for pumping water out of wells and other underground sources.
- Diaphragm Pumps: These pumps use a flexible diaphragm to move fluid through the pump. They are commonly used for pumping chemicals, food products, and other liquids.
- Gear Pumps: These pumps use interlocking gears to move fluid through the pump. They are commonly used for high viscosity liquids such as oil.

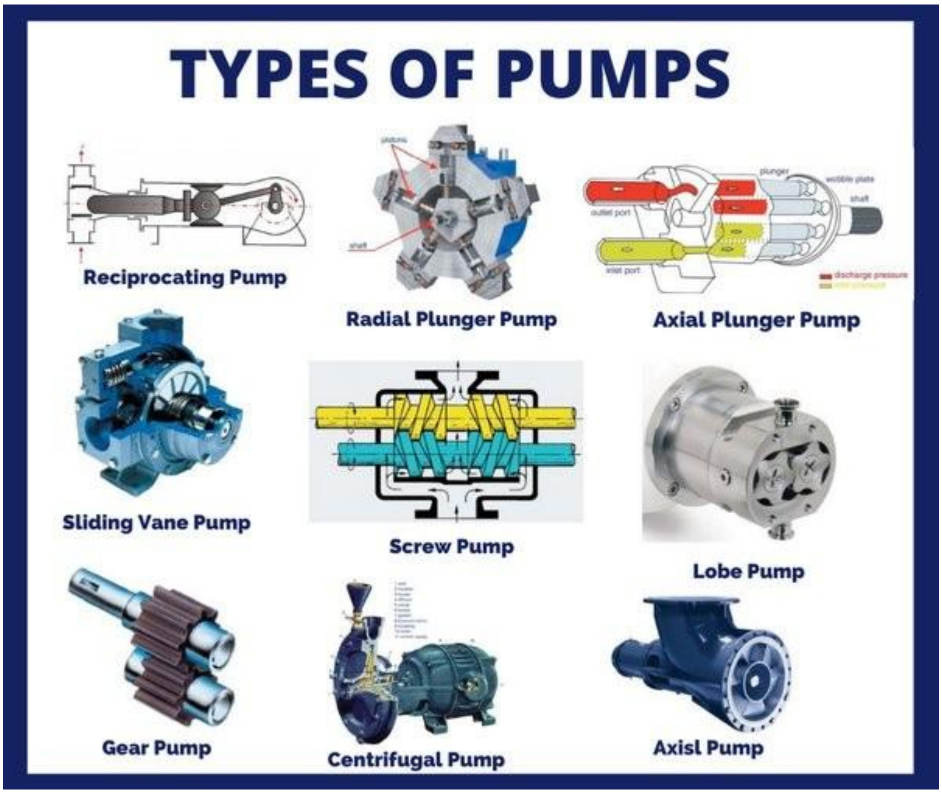


Figure E1. Examples of pumps for liquid transfer.

As the fluids used in absorption are relatively easy (uncompressible, nominal viscosity and density) without major corrosive components, the simple and robust *centrifugal pumps* are preferred. The main draw-back is that controlling the flow by adjusting the rotation speed does not provide a linear control curve (see Figure E2): very often the flow rate is controlled by adding a control valve and letting the pump rotate at a fixed speed.

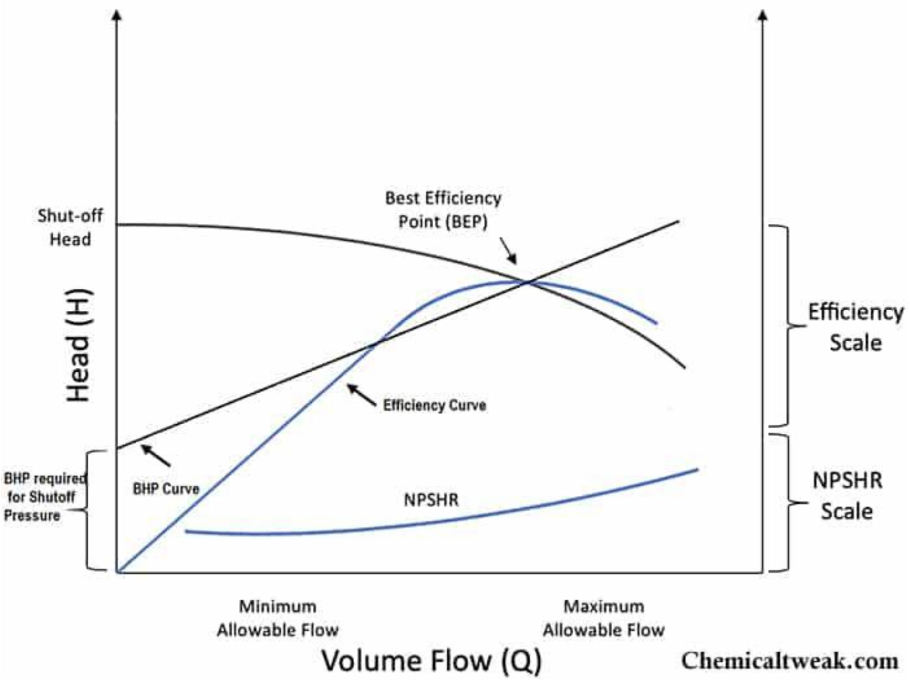


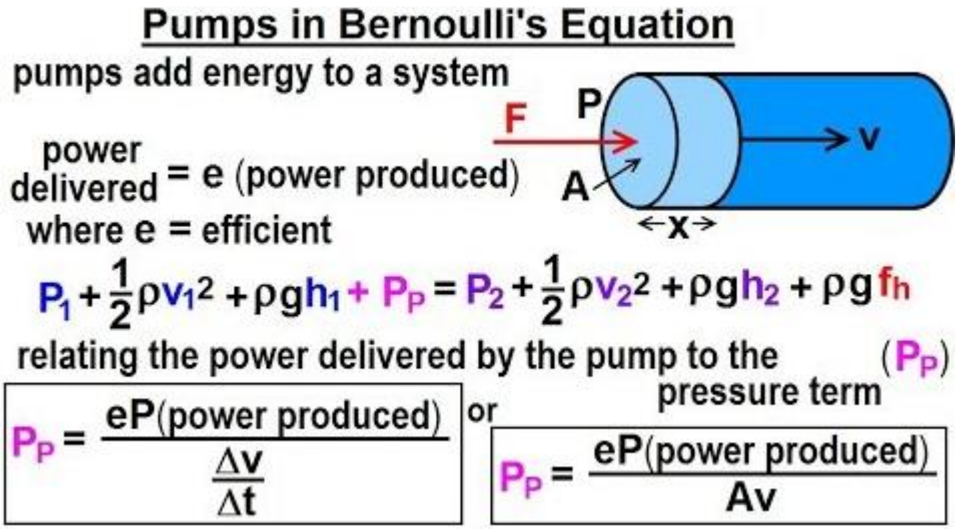
Figure E2. Pump curves for a centrifucal pump.

As can be seen from Figure E2, the pressure (head) the pump provides reduces as the flow rate in increased. Thus there is a point where the pump efficiency is the highest, known as *BEP*. If the pump is designed and run at this point ±20 %, the power consumption can be minimized: running the pump at full and restricting the flow provides a loss. However, the energy consumption for the pumping in the absorption system is generally so low that using control valves is justified.

The line marked as *NPSHR* defines the minimum pressure needed at the pump intake to avoid *cavitation* (a pressure where the fluid starts to boil and produce gas bubbles, which lower the efficiency and cause erosion).

The pump construction may be of steel or plastic: plastics endure better corrosive fluids but are more at risk of wear.

Pumps and pressure generated can be described with the Bernoulli's equations, see Figure E3.



Pumps in Bernoulli's Equation

pumps add energy to a system

power delivered = e (power produced)

where e = efficient

$$P_1 + \frac{1}{2}\rho v_1^2 + \rho g h_1 + P_P = P_2 + \frac{1}{2}\rho v_2^2 + \rho g h_2 + \rho g f_h$$

relating the power delivered by the pump to the pressure term (P_P)

$$\boxed{P_P = \frac{eP(\text{power produced})}{\frac{\Delta v}{\Delta t}}} \text{ or } \boxed{P_P = \frac{eP(\text{power produced})}{Av}}$$

Figure E3. The Bernoulli's equation for pumps.

Metal structure

Plastic structure

Figure E4. Examples of centrifugal steel and plastic pumps.

Blowers

A blower is a device which is capable of providing a pressure increase to a gas. A blower can be *radial* or *axial*, depending on the orientation of the blower wheel, see Figure E5. The main parts of an industrial radial blower are shown in Figure E6.

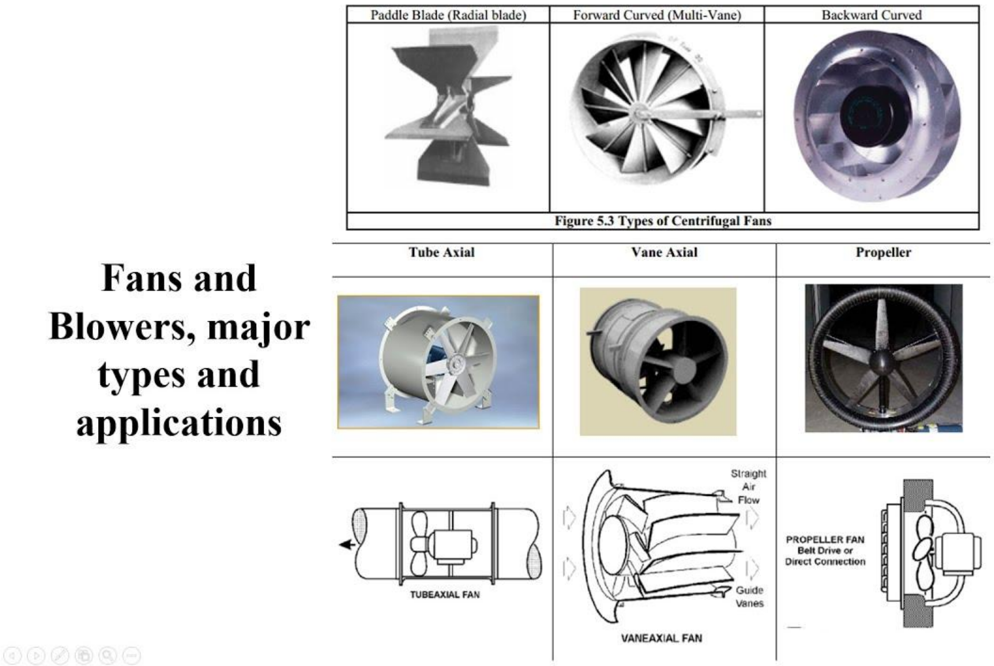


Figure E5. Fans and blowers.

The difference between a pump and a blower is that the fluid is gas, which is compressible. This means that some of the energy will be used to heat the gas: in a constant mass and volume system, if the pressure is increased, the temperature must also increase, see equation E1.

$$p\,V = N\,R\,T \qquad (E1)$$

Where	p	pressure, [Pa]
	V	volume, [m^3]
	N	molar mass, [kg/kmol]
	R	molar gas constant, 8.314 [J/mol K]
	T	temperature, [K].

The energy needed for the gas pressure increase is usually calculated by using the blower efficiency curve, volumetric flow rate and pressure increase, see Figure E6.

$$P = \frac{V \cdot \Delta p \cdot 10^{-3}}{\eta}$$

with:

P = Power requirement for fan [kW]
V = Quantity of gas delivered [m^3/s]
Δp: =Total increase of pressure in fan [Pa]
η = Fan efficiency according to fan curve [%]

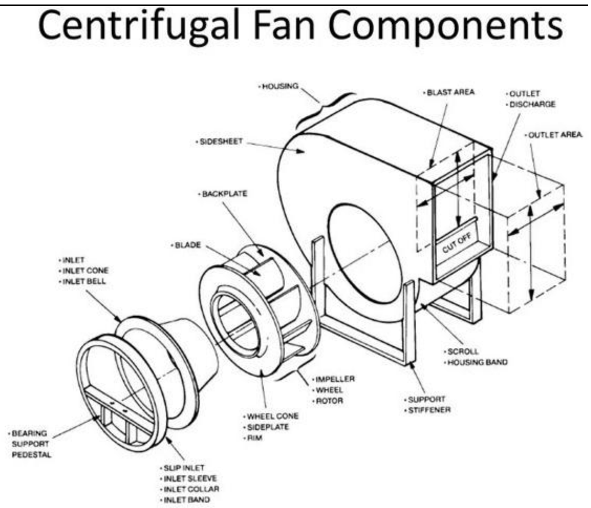


Figure E6. Compression equation and parts of a centrifugal fan.

As the biogas is flammable, an ATEX (refers to the hazard of explosive atmospheres occurring in the workplace due to the presence of flammable gasses or combustible dust mixed in air, which can give rise to the risk of explosion) rated blower is needed, see for instance Figure E7 for image and specs.

Model: **ATEX-LD 022 H43 R15**
Power supply: 1.5 (kw)
Air flow: 210 (m3 / h)
Vacuum: – 200 (mbar)
Pressure: 190 (mbar)
Weight: 50 (kg)
Voltage: 200-240 (V) / 345-415 (V) three phase
L * W * H: 352*360*367 (mm)
Running time: 24 hours non-stop
Stage: 1 stage / 1 impeller
100% copper wire, high quality bearing, low noise

Figure E7. Example of a biogas blower with ATEX rating.

Valves

A valve is an armature which restricts or closes a flow in a pipe, see Figure E8 for examples. Valves can be manually operated or equipped with an actuator (Figure E9). Actuators are needed for remote operation and control. Special valves include check valves (flow only to one direction), safety valves (open automatically at a pre-determined pressure) and multiple-way valves which direct flow into several pipes.

Figure E8. Different types of valves.

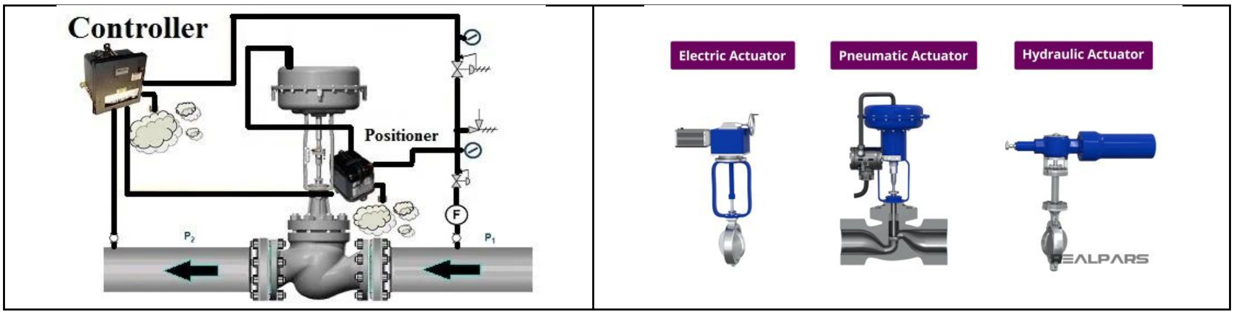


Figure E9. Flow control principle and three types of valve actuators.

Depending on the design and pipe selection, the valves can be made of metal or plastic.

Piping

Piping is needed to transfer fluids. Piping design general consideration involves determining the most efficient and effective layout of pipes, selecting appropriate materials and fittings, calculating pressure drops and flow rates, and ensuring the system meets safety and regulatory requirements. It also includes consideration of factors such as temperature, pressure, corrosion, and mechanical stress.

The goal of piping design is to create a system that is reliable, cost-effective, and easy to maintain, while meeting the specific needs of the application for which it is designed.

There are many general and engineering considerations while designing a piping layout of any plant (see Figure E10 for an example). Some of them are as follows:

- Pipe spacing
- Flange installation
- Valve installation and operation consideration
- Accessibility
- Piping arrangement and pipe routing (collision assessments)
- Slope piping, free drain piping, no pockets piping
- Aim for symmetrical piping.

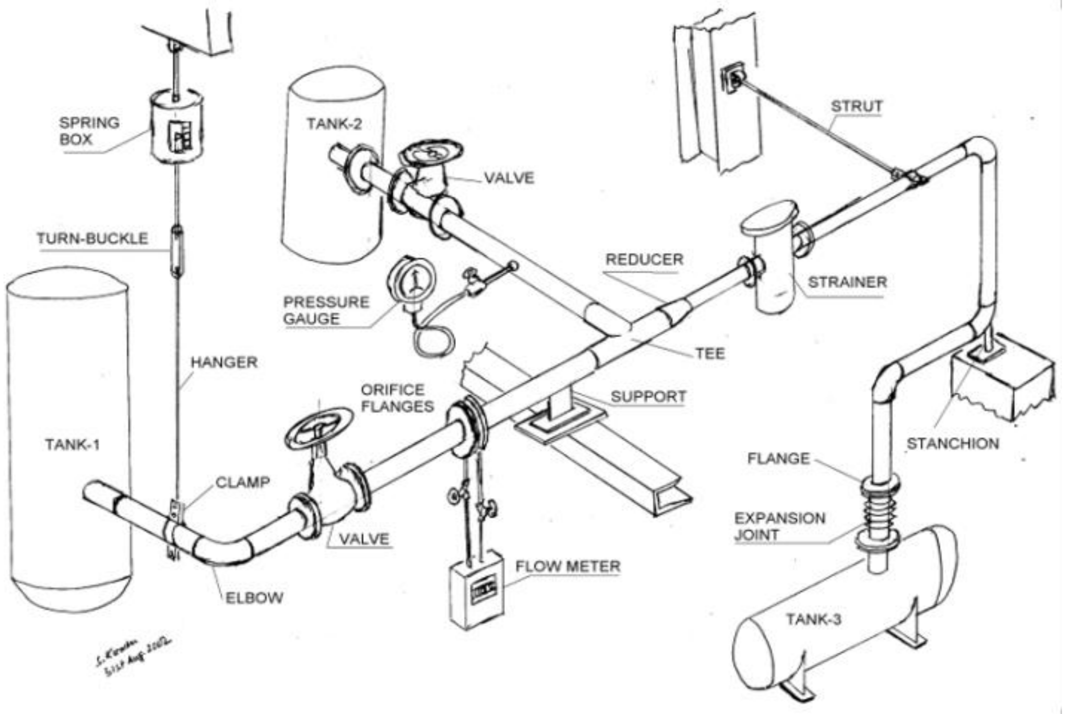


Figure E10. Example of a pipe system.

There are two types of pipes at the absorption system: gas pipes and liquid (absorbent and heating/cooling fluid) pipes. Pipes are usually dimensioned according to flow velocity: gases may have a greater velocity because the pressure drop is lower due to lower viscosity. Common figures are <10 [m/s] for gases and <1 [m/s] for liquids. A pipe line list (see Table E1) is a useful tool together with the PID drawing and layout images/models (isometric drawings).

Table E1. Pipe line list for the Machtech A1000.

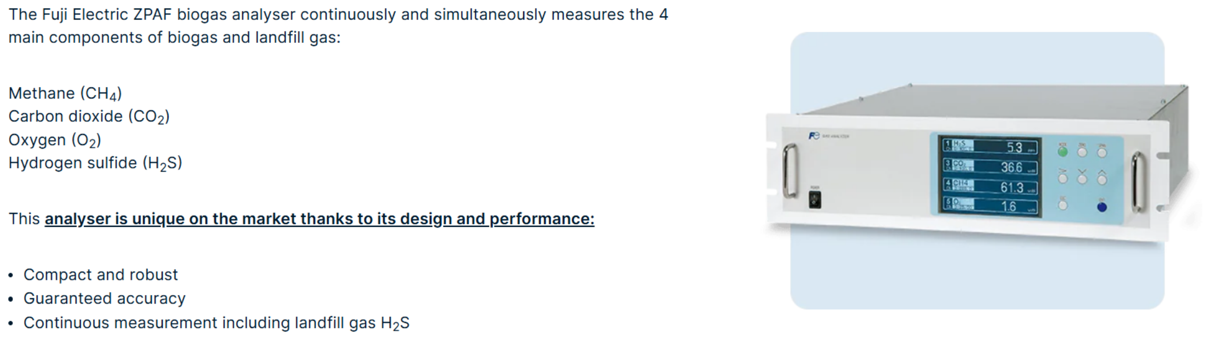
Line	Linecode		From	To	DN	inner ø	PN	Material	Operating temp. °C	Insulation mm
1	BGA	-001	Input	P-001	100	107.1	10	10H2A	20	
2	BGA	-002	P-001	K-001	100	107.1	10	10H2A	20	
3	CH4	-003	K-001	Out	65	82.5	10	10H2A	20	
4	AMW	-004	K-001	P-002	40	43.5	10	10H2A	20	
5	AMW	-005	P-002	W-001	40	43.5	10	10H2A	20	
6	AMW	-006	W-001	K-002	40	43.5	10	10H2A	80	50
7	AMW	-007	K-002	P-003	40	43.5	10	10H2A	90	50
8	AMW	-008	P-003	W-003	40	43.5	10	10H2A	90	50
9	AMW	-009	W-003	K-002	40	43.5	10	10H2A	95	50
10	AMW	-010	K-002	P-002	40	43.5	10	10H2A	95	50
11	AMW	-011	P-002	W-001	40	43.5	10	10H2A	95	50
12	AMW	-012	W-001	W-002	40	43.5	10	10H2A	95	50
13	AMW	-013	W-002	K-001	40	43.5	10	10H2A	95	50
14	CWA	-014	W-004	W-002	40	43.5	10	10H2A	10	50
15	CWA	-015	W-002	P-005	40	43.5	10	10H2A	20	50
16	CWA	-016	P-005	W-004	40	43.5	10	10H2A	20	50
17	HWA	-017	W-003	D-001	40	43.5	10	10H2A	95	50
18	HWA	-018	D-001	P-004	40	43.5	10	10H2A	95	50
19	HWA	-019	P-004	W-003	40	43.5	10	10H2A	95	50
20	CO2	-020	K-002	Out	100	107.1	10	10H2A	90	50

Instrumentation

The need for getting accurate information about the state of the process dictates the type and level of instrumentation. The main measurements which are needed to control the process include:

- The quantity (mass flow rate) and quality (pressure, temperature, composition) of the biogas at the absorber inlet.
- The quantity (mass flow rate) and quality (pressure, temperature, composition) of the biomethane at the absorber outlet.
- The quantity (mass flow rate) and quality (pressure, temperature, composition) of the CO_2 at the desorber outlet.
- Flow rate, pressure and temperature of the absorbent in different locations.
- Flow rate, pressure and temperature of the heating and cooling fluids.

Gas composition can be measured by periodic sampling and analyses, but this is not suitable for process control. There are analyzers which are dedicated to biogas, such as the Fuji Electric shown in Figure E11.



The Fuji Electric ZPAF biogas analyser continuously and simultaneously measures the 4 main components of biogas and landfill gas:

Methane (CH_4)
Carbon dioxide (CO_2)
Oxygen (O_2)
Hydrogen sulfide (H_2S)

This **analyser is unique on the market thanks to its design and performance:**

- Compact and robust
- Guaranteed accuracy
- Continuous measurement including landfill gas H_2S

Figure E11. Fuji Electric continuous biogas quality measurement system.

Temperatures are measured with *temperature transmitters*, which can be selected according to Table E2.

Table E2. Temperature sensor codes and explanations.

Code Type	Conductors Alloys (+/-)	Sensing Temperature	Sensitivity (µV/°C)
E	Nickel Chromium / Constantan	-40 to 900°C	68
J	Iron / Constantan	-180 to 800°C	55
K	Nickel Chromium / Nickel Aluminium	-180 to 1300°C	41
N	Nicrosil / Nisil	-270 to 1300°C	39
T	Copper / Constantan	-250 to 400°C	43
R/S	Copper / Copper Nickel Compensating	-50 to 1750°C	10
B	Platinum Rhodium	0 to 1820°C	10

As the temperatures in the system are relatively low, generally below 100 °C except in the boiler, standard PT-type thermocouples are inexpensive and robust devices.

Pressures are measured at two main ranges:

1. Low-pressure in gas, usually between -100 and +200 Pa.
2. High pressure in the amine, cooling and heating systems, between 1 and 6 [bar(a)]

The pressure measured can be as (see also Figure E12):

A. Gauge pressure (the pressure relative to atmospheric pressure)
B. Absolute pressure
C. Pressure difference (usually measured over a piece of equipment).

Figure E12. Three different pressures in a system.

Flow measurement can be based on any of the following principles:

- Electromagnetic flow meters
- Coriolis flow meters
- Ultrasonic flow meters
- Thermal mass flow meters
- Turbine flow meters
- Vortex flow meters
- Differential pressure flow meters
- Variable area flow meters.

Figure E13. Examples of flow measurement devices.

The fluids in the absorber system are not difficult to measure, so for instance a device shown in Figure E14a would suit well. For liquids, the one in Figure E14b would suffice.

a) For biogas

b) For liquids

Figure E14. Flow measurements for biogas and liquids in the system.

The signals from the instruments may be collected as analog (V or mA) and/or in digital form, and then translated to values shown in the HMI/GUI. This is described in detail in a separate Annex.

1.0 INTRODUCTION

Test systems for operation of the slope bottom reactor and performance of different amines suitable for CO_2 absorption has been recommended as an additional part of the VAMK project. The equipment needed can be rented and built by using used components Karhubetoni Oy possesses. The only things needed from outside are the premises, feedstocks and chemicals (gases and liquids), worker(s) can be supplied by the project.

2.0 TEST SYSTEMS

Two different systems are needed, one for the slope bottom reactor and other for the absorption system.

2.1 Slope Bottom Reactor

The main issues related to the slope bottom reactor are ability to dilute the difficult materials, especially the ones coming from greenhouses, see Figure 1 for reference.

Figure 1. Organic material from greenhouses, including the plastic strings used for holding the branches.

One simple method for the testing is to use a tank available from Karhubetoni Oy, see Figure 2. The test system is illustrated in Figure 3.

Figure 2. A steel tank which could be used for testing the leaching and dilution of organic materials.

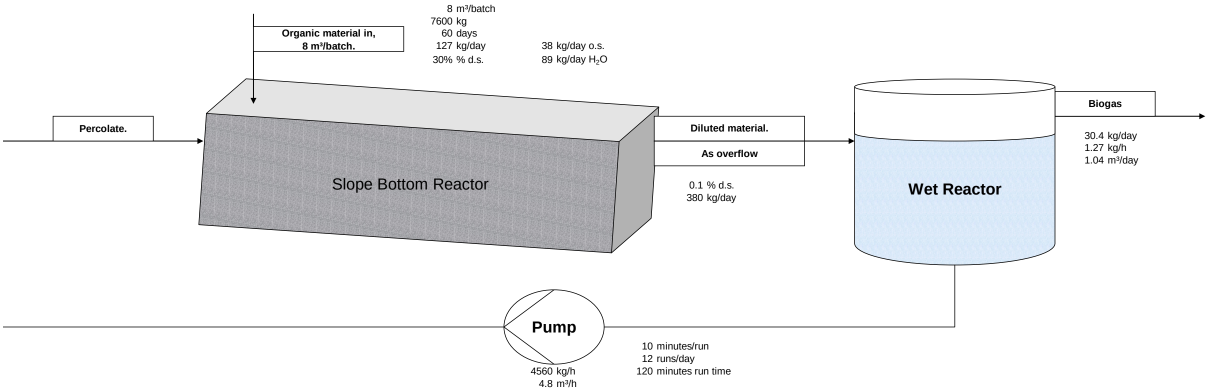


Figure 3. Proposed test system and dimensioning of the flows.

2.2 Absorption Tests

The test system mimics the full-scale absorption system already defined at the project: the same PID can be used as the basis, and by taking only the minimal setup, costs can be minimized. The minimal system has:

- Absorber, 2 m x 0.2 m, available from Ductor Oy. Rented (VAMK).
- Desorber, 1 m x 0.2 m, available from Ductor Oy. Rented (VAMK).
- Gases as pressurized bottles, 1 bottle for CO_2 and one for CH_4. Rented (VAMK). (E-Metaani CH4 N45 50L 175bar DIN1 (woikoski.fi) and Hiilidioksidi - Woikoski).
- Liquid pumps, one for hot amine and one for cold CO_2 rich amine. Karhubetoni Oy.
- Heat exchangers, two units. Karhubetoni Oy.
- Burner for CH_4. Karhubetoni Oy.
- Gas and liquid lines with armatures. Karhubetoni Oy.
- Electrical cabinet and automation (Unitronics). Karhubetoni Oy.
- Measurements. Karhubetoni Oy.

A suitable location near Vaasa is needed: a wet laboratory would be best, but other premises are also possible. Space need is about 10 - 20 m^2. Rented (VAMK). The test system is illustrated in Figure 1.

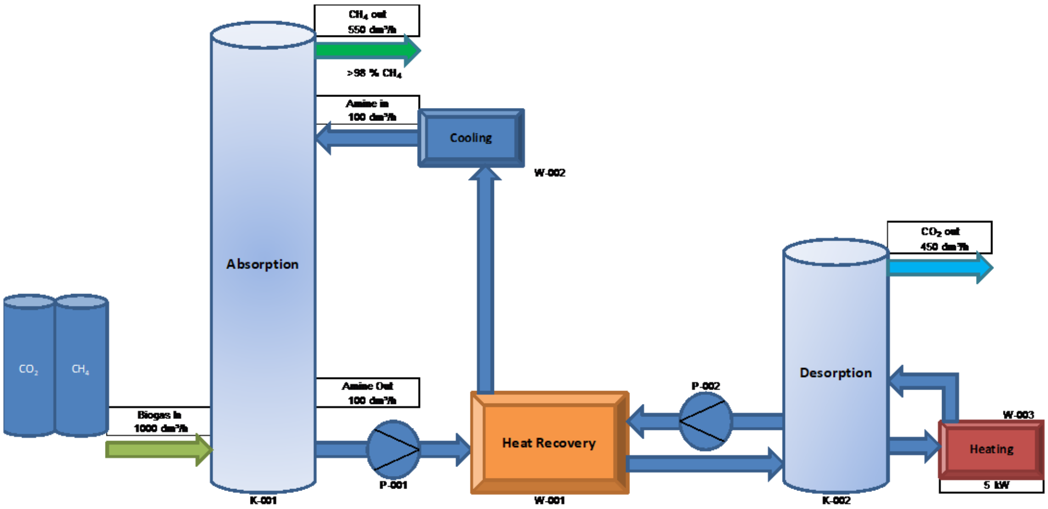


Figure 4. Illustration of the test system and main flows.

It is also possible to connect the test system to an existing biogas plant, or maybe even to the wet reactor for the slope bottom reactor.

3.0 TEST PROCEDURES

The two test systems can be totally separate, or connected so that the biogas produced in the slope bottom reactor test unit is taken into the amine stripper (semi-continuous operation).

3.1 Organic Materials

The mixture of organic materials (the matrix) is one of the key parts in testing of the slope bottom reactor. The proposed first mix could be a combination of greenhouse wastes, manure and grass. After the batch has been made, the top hatch is closed and pumping of percolate can begin. It is recommended that a batch of liquid from an operating biogas plant is added to bring the bacteria necessary for the digestion and following biogas production. Each batch is run until the flow of organic material stops (biogas production reduces), but no longer than two (2) months.

Liquid from the wet reactor is periodically pumped into the slope bottom reactor, the pumping frequency depends on the size of the pump. The biogas production is followed during the tests, as well as the pH and suspension density of the organic liquid (leachate). The material remaining in the slope bottom reactor is analyzed for composition (organic material, plastics, inorganic materials).

3.2 Amines

The tests can be done as follows:

- The two pumps are switched on and the flows are stabilized.
- The heater is started and the Desorption unit K-002 is heated to 80 °C.
- The gas flow is adjusted by hand valves to correspond the desired 1000 dm^3/h.
- The unit is run for one (1) hour.
- The gas compositions at the outlets are monitored.

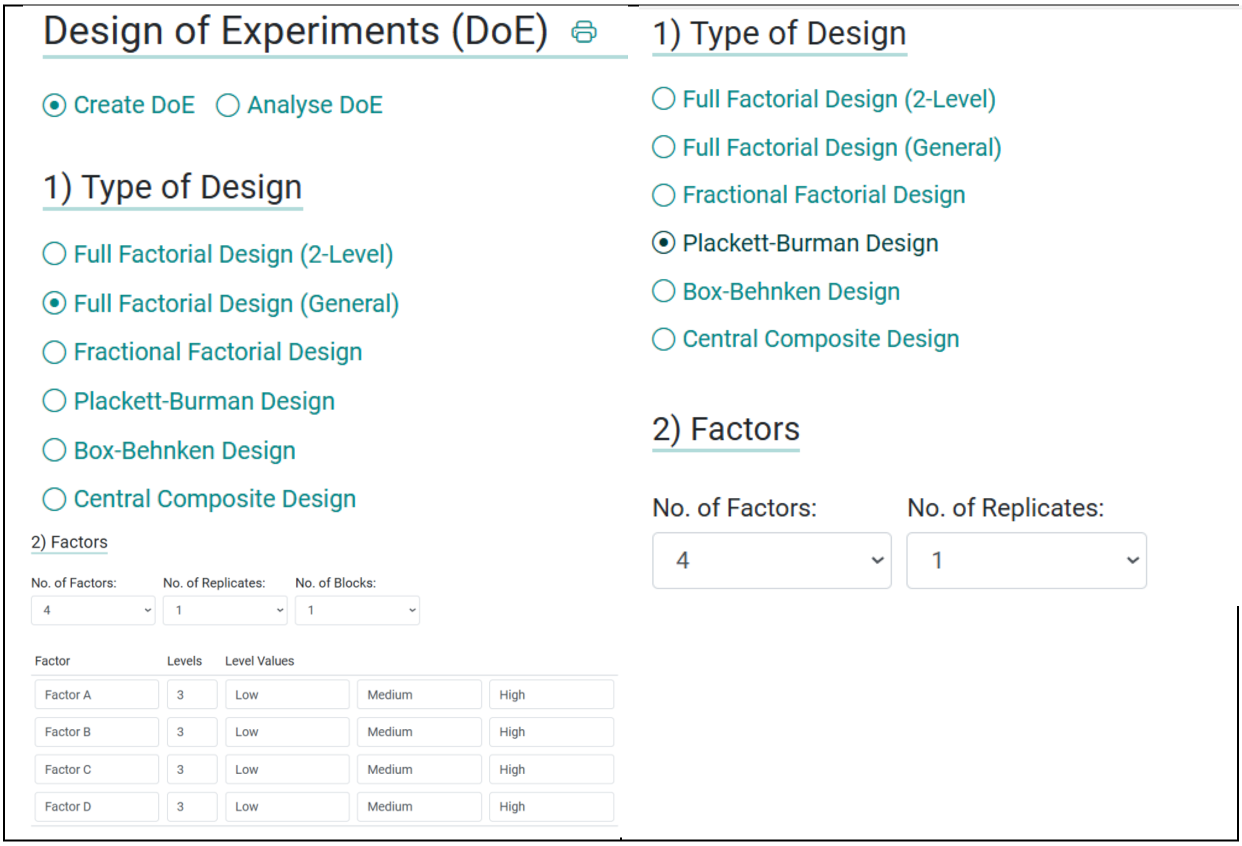
Several different amines and amine/water/booster liquid combinations, absorption and desorption temperatures, and flow rates (residence times) are tested according to matrix shown in Table 1.

Table 1. Proposed test matrix with full set of tests, 3^4 system, total 81 tests.

Test ID	Gas low dm³/h	Liquid flow dm³/h	CO_2/CH_4 -	Temperature °C
AAAA	Low	Low	Low	Low
AAAB	Low	Low	Low	Medium
AAAC	Low	Low	Low	High
AABA	Low	Low	Medium	Low
AABB	Low	Low	Medium	Medium
AABC	Low	Low	Medium	High
AACA	Low	Low	High	Low
AACB	Low	Low	High	Medium
AACC	Low	Low	High	High
…	…	…	…	…

A total of six (6) tests can be performed during a standard eight (8) hour working day. By doing a 3^4 test plan, all tests are not necessary, but a random order for tests is necessary. A calculator for different types of test reduction methods and following test matrix can be found for instance from Design of Experiments (DoE) Calculator- DATAtab. Table 2 shows an example of test reduction and randomization.

Table 2. Method for reducing the number of tests.



Design of Experiments (DoE)

● Create DoE ○ Analyse DoE

1) Type of Design

○ Full Factorial Design (2-Level)
● Full Factorial Design (General)
○ Fractional Factorial Design
○ Plackett-Burman Design
○ Box-Behnken Design
○ Central Composite Design

2) Factors

No. of Factors: 4
No. of Replicates: 1
No. of Blocks: 1

Factor	Levels	Level Values		
Factor A	3	Low	Medium	High
Factor B	3	Low	Medium	High
Factor C	3	Low	Medium	High
Factor D	3	Low	Medium	High

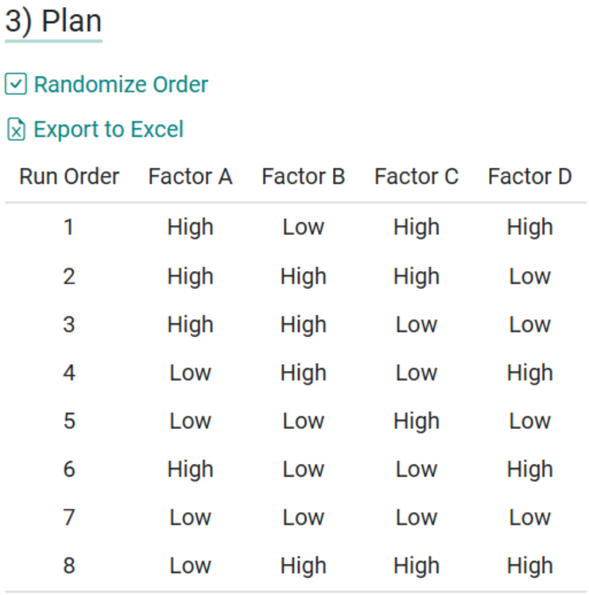
1) Type of Design

○ Full Factorial Design (2-Level)
○ Full Factorial Design (General)
○ Fractional Factorial Design
● Plackett-Burman Design
○ Box-Behnken Design
○ Central Composite Design

2) Factors

No. of Factors: 4
No. of Replicates: 1

Would require 81 tests!



3) Plan

☑ Randomize Order

Export to Excel

Run Order	Factor A	Factor B	Factor C	Factor D
1	High	Low	High	High
2	High	High	High	Low
3	High	High	Low	Low
4	Low	High	Low	High
5	Low	Low	High	Low
6	High	Low	Low	High
7	Low	Low	Low	Low
8	Low	High	High	High

Only 8 tests will provide sufficient data!

Some tests with medium values can be performed accordingly after the initial dependencies have been found. This procedure allows testing of different amines and mixes without expanding the number of test too much.

4.0 COSTS

As Karhubetoni already has most of the components needed for building of the two test systems, the costs are mainly related to transport of the equipment; some additional costs may be due to electrical connections and other work done by external experts. The equipment is located in two storages, one in Järvenpää and the other in Eura. Karhubetoni has a truck which can be used for the transport, so this cost is mainly related to fuel consumption and can be expressed in terms of €/km. Two days are needed as the number of driving hour/day is limited. The route is:

Järvenpää – Eura 188 km
Eura – Vaasa 242 km
Vaasa – Järvenpää 380 km
TOTAL 810 km
Price €/km 2,00 €
TOTAL 1 620 €

Two persons are needed for loading and unloading, salary is 320 €/day, summed cost is **1 280 €.**

So the loading, transport and unloading is 2 900 €.

It is estimated that approximately 2 000 € is needed for external experts, mainly for electrical connections and piping work.

5.0 LABORATORY TESTS/LEACHING

In order to determine the leaching/dilution rate for different materials in different liquids/percolates, a small-scale laboratory tests is proposed. This test could be done as follows:

- **12 glass vessels (decanters), each ½ litres with a gas-tight lid are needed. A small (1 – 2 mm) hole is punched on the lids.**
- **One piece of cucumber plant and one piece of tomato plant, about 10 cm in length is put into each decanter.**
- **Decanters are filled to the brim with liquids with varying composition, pH range from 5 to 12.**
- **Decanters are located in a warm ventilated place, preferably >30°C, with explosion protection (gas pressure may cause shattering of glass even though the small holes should release the pressure). There may be some smell.**
- **Decanters are photographed at the end of each test week.**
- **Dilution/leaching results are reported after two (2) months.**

Dimensioning of the Slope Bottom Reactor, Example #1

As the purpose is to use the slope bottom reactor(s) in an optimal way, the dimensioning can be based on the mass flow demand by the forward method described in the paper *Biogas Plant Basic Design* or based on the energy production target. By using the upgraded operation method where the organic mass is diluted from the bulk matrix to provide a continuous and nearly constant material flow into the wet reactor, the capacity of each reactor depends mainly on the desired residence time. For instance, if we take a reactor active volume of 500 m^3 and 80 % filling rate, we get

A. 400 m^3/batch of solid material.

By using the average moisture content of grass which is about 30 % and estimated density is 1 000 kg/m^3, we get

B. 120 000 kg solids and
C. 280 000 kg water per batch.

If we need about three (3) months residence time for the most demanding organics, and assume that the average hydraulic retention time in the wet reactor is one (1) month, we need 60 days as the residence time in the dry reactor. This calculation is based on the assumption that the easier a material is to dilute, less probable is the need for longer residence/reaction time, so what comes out first from the slope bottom reactor is easier to digest. The earlier numbers result to

A. 2 000 kg/day solids out at 10 % d.s., which needs
B. 18 000 kg/day water of which 4 700 kg/day comes with the feedstock, so the net input is 13 000 kg/day (560 kg/h).

If this diluted (and activated!) material is fed into a 2 500 m^3 wet reactor, and total of four (4) slope bottom reactors are used, the total feed is about 12 000 ton/a, providing up to 12 GWh worth of biomethane. See full calculation in Figure 1. An Excel model was made with main parameters highlighted in green, so further studies are relatively easy to conduct.

Annex G

Dimensioning of the Slope Bottom Reactor

Slope Bottom Reactors and Connection to Wet Biogas Process

Number of fermenters, dry		4				
Size of each fermenter		500	m^3			
Number of batches per year		6		60	days/batch	
Solids suspension density		800	kg/m^3	Solids content		30%
Beginning	Solids	120000	kg	24%		
	Water	280000	kg	4667	kg H_2O/day	
	Void	100	m^3			
Solids mass flow out		2000	kg/day	10%		
Per reactor		83	kg/h			
Water circulation		18000	kg/day	18	m^3/day	
Per reactor		750	kg/h	0.8	m^3/h	

13333	kg/day
556	kg/h

Number of fermenters, wet		1		30	Days	Availability	90%		
Size of each fermenter		2400	m^3			Hours/a	7884		
Number of batches per year		Continuous							
Solids suspension density		100	kg/m^3						
Solids mass flow in		8000	kg/day			Solids out	1920	kg/day	2.7%
		83	kg/h	Yield	80%		80	kg/h	
Water circulation		72000	kg/day	72	m^3/day		631	ton/a	
		3000	kg/h	3.0	m^3/h	Yield	82%		
CH_4	37% m-%	2370	kg/day	3762	m^3/day		1235979	m^3/a	55% CH_4
CO_2	63% m-%	4030	kg/day	3100	m^3/day		1018256	m^3/a	45% CO_2

12.4 GWh

280

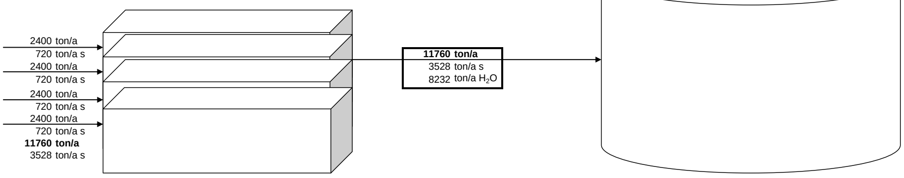


Figure 1. Example calculation of slope bottom reactors and connection to a wet reactor.

Each slope bottom reactor could have initial dimensions of 20 m (L) x 8 m (W) x 4 m (H) as the active volume, images to be added. The height depends mainly on the machinery used for the filling and emptying of the reactors. If the four reactors are built side by side, a common water/slurry collection basin can be integrated at the back of the building. By using several overflow openings equipped with string prevention grates could be used for controlled transport of slurry from the reactors: water level in each reactor dictates the flow. The suspension density in the basin can be lowered by adding water if necessary, and monitored by the torque needed by the pump(s).

One of the main benefits of the slope bottom reactor is the capability of handling different materials with varying moisture content: traditionally dryer materials have been wetted to achieve an optimal dryness, which is no longer necessary. More biomethane can be produced by adding materials with higher organic material content, if available.

17.8.2025

Feasibility Calculator

Biogas Oy

Biogas fermentation

50 000 ton/a 26 % d.s. 73 % yield

Gate fees/costs:	-35	€/ton
Nitrogen fertilizer price:	84	€/ton
Solid fertilizer price:	100	€/ton
Methane:	4 134 824	m³N/a

Availability:	95 %	
	8 322	h/a
Heat price:	20	€/MWh
El price:	125	€/MWh

OPEX

Maintenance:	223 700	€/a
Personnel:	837 000	€/a
Own energy use:	684 000	€/a
Chemicals:	138 000	€/a
Insurances:	74 600	€/a
Other costs:	180 100	€/a
TOTAL:	**2 137 400**	**€/a**

PROFIT:	**2 615 600**	**€/a**

ROI:	**17.5**	**%**

Gate fees/costs:	-700 000	€/a
Nitrogen fertilizer:	284 232	€/a
Solid fertilizer:	608 086	€/a
Biomethane:	3 721 342	€/a
Heat sales:	164 704	€/a
Coal sales:	674 664	€/a
TOTAL:	**4 753 000**	**€/a**

CAPEX		120 %
Planning and commisioning	1 196 000 €	10 %
Site costs	160 160 €	1 %
Substrate preparation&dosage	696 000 €	6 %
Fermenter	2 638 000 €	21 %
Pumping equipment	616 000 €	5 %
Heat exhanger	564 000 €	5 %
Gasholder	696 000 €	6 %
Gas upgrade	3 072 000 €	25 %
HTC process	2 102 000 €	17 %
Electric installation	1 866 000 €	15 %
Thermal insulation	508 000 €	4 %
Assembly and construction	800 000 €	6 %
	14 914 160 €	

17.8.2025

Feasibility Calculator

Stripper 1000 mm

🟩	From MEB
🟦	Free variable

Availability:	**95 %**	
	8 322	h/a
Own gas use:	**0 %**	

Production:		
Biogas as methane:	10 000	MWh/a
Nitrogen fertilizer:	23	ton/a
Biogas from amine	2 681	ton/a
Consumptions:		
Power:	250	MWh/a
Heat:	750	MWh/a
Amine:	50	ton/a

Pricing:		
Biogas price:	**70**	€/MWh
Biomethane price:	**100**	€/MWh
Amine price:	**1 500**	€/ton
Heat price:	**70**	€/MWh
Electricity price:	**120**	€/MWh
Nitrogen price:	**1 000**	€/ton

OPEX

Maintenance:	14 000	€/a
Personnel:	40 000	€/a
Energy:	82 500	€/a
Chemicals:	75 000	€/a
Insurances:	5 600	€/a
Other costs:	10 855	€/a
TOTAL:	**228 000**	**€/a**
PROFIT:	**113 200**	**€/a**
ROI:	**25.2**	**%**

Incomes:

Biomethane:	300 000	€/a
Nitrogen fertilizer:	22 500	€/a
Biogas:	18 700	€/a
TOTAL:	**341 200**	**€/a**
Simple payback:	**4.0**	**a**

CAPEX		
Planning and commisioning		25 000 €
Site costs		15 000 €
Substrate preparation&dosage		15 000 €
Reactors		85 000 €
Pumping equipment		10 000 €
Heat exhanger		15 000 €
Gasholder		25 000 €
Electric installation		32 000 €
Thermal insulation		12 000 €
Assembly and construction		45 000 €
Total		**279 000 €**
Payment		450 000 €
Profit		171 000 €
Payment (Annuity)		7 458 €
Loan time, a	6	89 494 €
Interest, %/a	6 %	