REPORT

EUDP PROJECT

FLOWGAS 14-1 / 64012-0151

September 2015

TK Energy ApS

Preface

This document is the final report of the project FLOWGAS (EUDP 14-1 / 64012-0151).

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1. **Introduction**

This report introduces the technology development carried out by TK Energy ApS between 2013 and 2015 on biomass handling and dosing from storage to injection unit, in both atmospheric and pressurized facilities. The technology is intended to be used in biomass gasification processes.

The work in the FLOWGAS project was redefined during the project. The first purpose of the project was to develop an atmospheric entrained flow gasifier. During this project another project with a pressurized entrained flow gasifier was granted by EUDP and it was decided to change the remaining part of FLOWGAS to support this new project.

Based on this change the project has been built up of different part that will be presented in this report in the following four sections.

- Primary dosing bin

This report starts with the presentation of an atmospheric dosing system developed partly through a student project. The system provides up to 100 kg/h of wood powder and was intended to be used for feeding a downsizer in the French company CEA (Alternatives Energies and Atomic Energy Commission).

- Atmospheric fuel preparation, dosing and injection

The document continues with the presentation of the work following the original purpose of the FLOWGAS project, supported by the Danish Energy Agency, which aims to demonstrate an atmospheric 10 MWth gasification process. This project is linked with the first as the dosing system is based on the design and experiments carried out in the first project.

- Pressurized dosing and injection facility

The report presents then an experimental facility for dosing and injection of wood powder under pressure (40 bar). The results and technology of the atmospheric part have been key advantage for the sale of this experimental facility to the French company CEA.
The manufacturing of this machine has given the possibility to TK Energy to test and validate its dosing technology under pressure.

- Sludge dryer

The final part of the FLOWGAS project was utilized to developing a biomass dryer. The dryer will be the first part to be built in the pressurized entrained flow project. The part includes considerations about the critical design issues in the dryer.

2. Context

TK Energy is specialized in handling and gasification of biomass and waste. The FLOWGAS project had the purpose of demonstrating a complete supply line from material storage to gasification at atmospheric pressure into an entrained flow reactor.
The supply line of the process is today the key for making wood gasification more competitive. Supply and feeding lines where components are energy consuming (lock hoppers, transport gas for injection) are a brake to gasification processes.
Post-gasification technology is however working efficiently and hardly improvable.

TK Energy has developed its own gasification process system. The diagram below shows the process steps for supplying biomass or waste into a pressurized entrained flow reactor.
The colour code is as follows:

- In blue are shown the steps where technology has been developed, produced and tested.
- In grey are shown the steps where technology has been developed but not tested.
- In green is shown the pressurisation step because TK Energy has previously developed and tested a pressurized feeder.

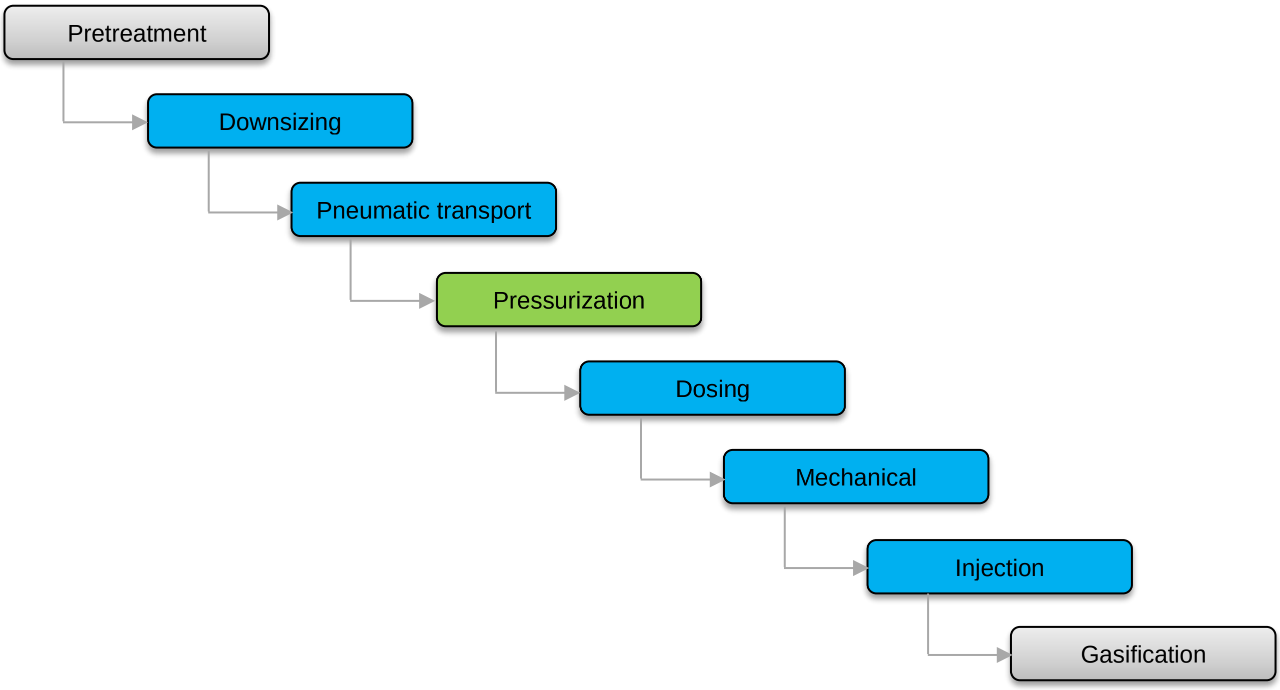


Figure 1 Process steps from raw fuel material to gasification

The report presents the work carried out on the blue and grey steps of the gasification process. The versatility of the technology has been the focus of TK Energy through these projects.

Mechanical properties and composition of waste and biomass can vary a lot and therefore the technology has to be robust and be able to handle these changes. Components have normally been tested with materials having different properties, among beech wood chips, saw dust, sewage sludge, micrometric wood powder and torrefied wood powder.

3. **Dosing bin prototype 100 kg/h**

In the beginning of the FLOWGAS project, a student project was conducted in parallel to the FLOWGAS project. The purpose of this student project was to develop a dosing bin for dosing biomass. The development gave strong background for the further development of the dosing devices build in the FLOWGAS project. Therefore the report from the student project is presented here. It includes description and a brief experimental report.

The main conclusions that can be drawn from this project are:

- An efficient mixing device has been designed. It ensures an optimal filling of the dosing screw and prevents material from bridging.
- Changes in the level of material in the dosing bin can result in changing the density of the material and so in the mass flow: a regulation of the level in a dosing device in therefore necessary.
- With this design, different types of powders can be delivered with a flow variation smaller than 5%.

3.1. Technical specifications

The technical requirements for the feeding system are as follows:

- Type of material to be fed: micrometric wood powder
- Bulk density of the powder ~ 200kg/m3
- Mass flow: from 6 to 60 kg/h
- Mass flow fluctuations: 5% max
- Tank volume ~100 L
- Outlet: vertical pipe ø60 mm

3.2. Description of the feeding system

This part introduces the feeding system and its components, its specifications and its operating principle.

3.2.1. Specifications

- Total dimensions: W580mm x L870mm x H1440mm
- Flow range: 15-100 kg/h with the F315 powder. The flow range depends on the powder used because this system is a volumetric dosing system. A slower motor will be provided as soon as the CEA will have tested the system with its own wood powder and will know the exact speed needed.

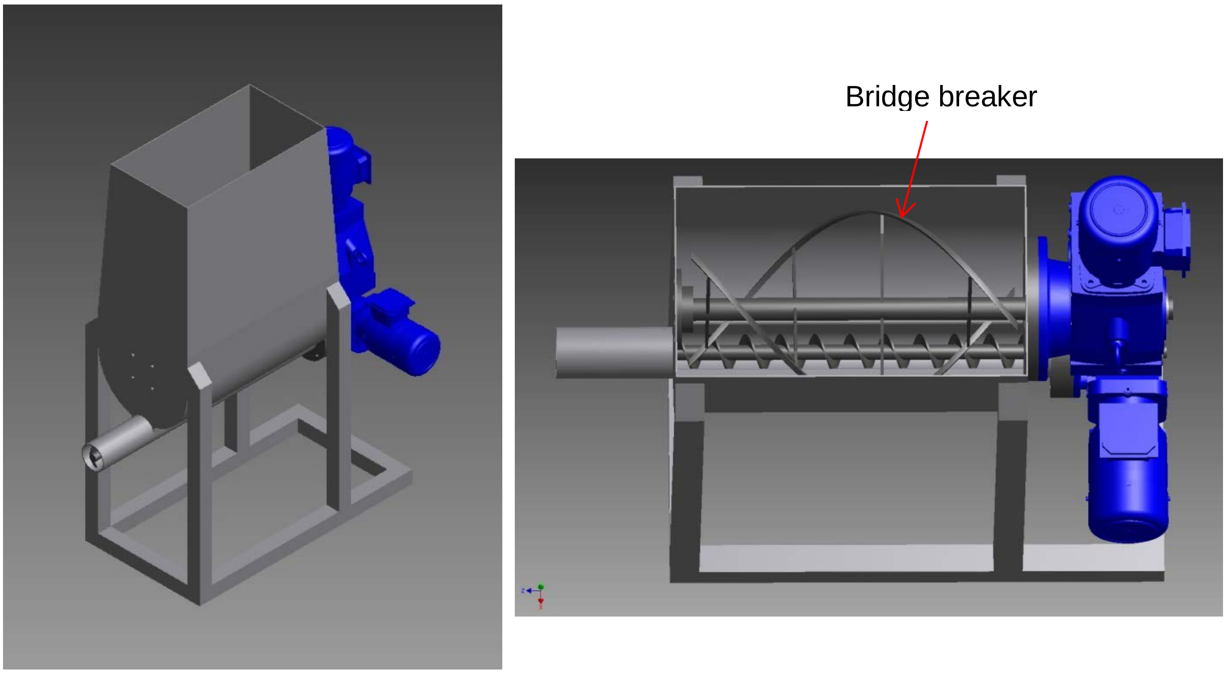


Figure 2 Sketches of the dosing bin 100 kg/h

3.2.2. Design and components

The feeding system is composed of:

- A tank:
    - Volume ~140L
    - Dimensions of the inlet, on the top of the tank: 300 mm x 550 mm
    - A door is bolted on the top of the tank. A flange, with a 270 mm inside diameter, permits to charge the material into the tank.
- A feeding screw:
    - The screw located in the bottom of the tank permits to carry the material from the tank to the outlet.
    - Pitch: 55 mm
    - Outside diameter: 64 mm
    - Inside diameter: 26.5 mm
    - Volume per revolution
    - Only in the screw : 0.147 L
    - In the pipe : 0.278 L
- A pipe for the screw:
    - Outside diameter : 89 mm
    - Inside diameter : 81 mm
    - The screw is placed in this piece of pipe, welded in the bottom of the tank. In the inside of this pipe, three counter-screws are welded for a better transportation of the material (cf. Patent FR2867463).
    - The counter-screws are perpendicular with the flights of the screw
    - Width of the counter screw : 8 mm

  - Thickness of the counter screw : 5 mm
- A bridge breaker
  - The bridge breaker mixes the material which is in the tank. The function of the bridge breaker is to avoid the formation of arch of material above the screw and ensure a maximal filling rate of the screw.
  - Shape : 2 helical blades, pitch: 900 mm
  - Diameter: 340 mm
  - Diameter of the shaft: 40 mm
- Two motors:
  - Two asynchronous geared motors are used to turn both the screw and the bridge breaker. They are directly coupled with the shafts.
  - Screw gearmotor: NORD GEAR, SK912172AF/3D-71S/4 3D, 0.25 kW, velocity at 50Hz: 33 r/min, 72.2 Nm
  - Bridge breaker gearmotor: NORD GEAR, SK9022.1AF/3D-71L/4, 0.37 kW, velocity at 50 Hz: 6.3 r/min, 559 Nm

3.2.3. Prototype

Before producing the final version, a prototype of the feeding system has been developed. The goal of this prototype was to validate the working principle and the design, and to characterize the flow range and its accuracy.

Figure 3 Picture of the prototype during an experiment

3.2.4. Data acquisition system

The tests have been done on the prototype version. To measure the mass flow, the feeding device has been put on a weight bridge, composed of 3 weight sensors (NTT-9110).

Figure 4 Picture of the load cells

The figure below shows the data acquisition system:

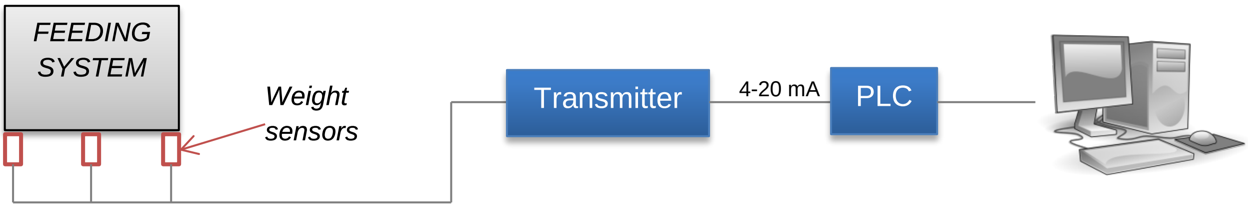


Figure 5 Data acquisition system

Thanks to this system, we have the weight evolution in function of the time. The transmitter filters the signal and amplifies it to a 4-20 mA signal. The PLC transmits by Ethernet connection the weight and the calculation of the mass flow to the computer.

3.2.5. Wood powder used for the tests

The powder used for the experiments is the ‘F315 powder’ produced by SPPS and delivered by CEA to TK Energy in November 2012. The bulk density of F315 powder is variable in function of the compression rate. The CEA measured a density of 220 kg/m3 for a compression rate of about 35%.

The feeding system is a volume dosing system, meaning that it doses a volume flow depending on the velocity of the screw. The mass flow has to be calculated from the density of the material fed.

TK Energy does not have the powder that the CEA will use with this feeding system. The mass flow will be different if the CEA uses a different powder and these results of mass flow are only valid for the F315 powder.

3.3. Tests and results

This part shows the experiments done to characterize the flow of the feeding system.

3.3.1. Function tests

In a first time, several function tests have been done to prove that the system could feed different powders at different flows.

After these tests, several improvements have been made:

Modification of the bridge breaker blades: Initially, the bridge breaker was composed by two flat blades (cf. figure 5)

Figure 6 First bridge breaker version

This shape of blades was efficient but the torque required to turn the bridge breaker was very high, due to the big quantity of powder moved by this flat blades.

Others blade shapes have been tested but finally a helical shape has been chosen (cf. figure 6). Each blade does half a revolution.

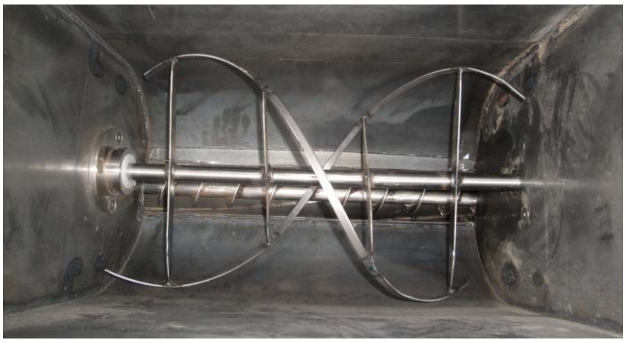


Figure 7 Helical bridge breaker prototype

This bridge breaker is very efficient and thanks to its shape, it needs a constant torque to turn. A constant torque is better for the lifetime of the motor.

The distance between the bridge breaker and the screw has been reduced.

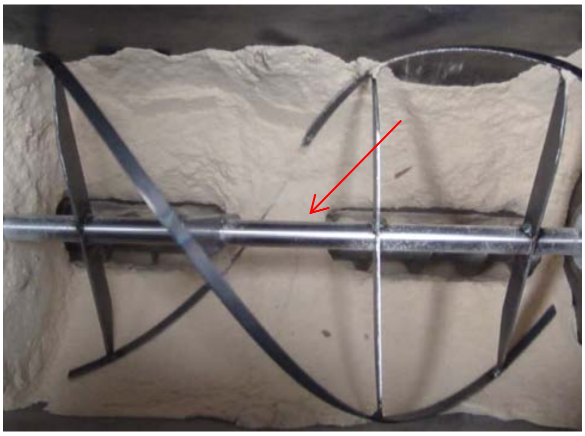


Figure 8 Picture of powder bridge above the screw

This picture shows a bridge of powder between the bridge breaker and the screw, because the space between the two components is too large. It also shows a lot of powder on the sides of the tank.

The position of the screw has been pulled up to be closer to the bridge breaker to avoid this kind of bridges. To reduce the quantity of powder staying on the tank walls, the diameter of the bridge breaker has also been increased to be closer to the wall.

These modifications improved a lot the efficiency of the bridge breaker which avoids the creation of bridges of powder. Its shape, its dimensions and its velocity are now perfectly adapted with the rest of the feeding system.

3.3.2. Experiment #1 – Effect on powder properties

A first experiment has been done to know if the feeding system modifies the properties of the wood powder.

This first experiment was to do 6 tests, at the same screw velocity, by using the same powder again at each test. The supply frequency of the motor was 100 Hz. The following graph shows the average flow in function of the test number.

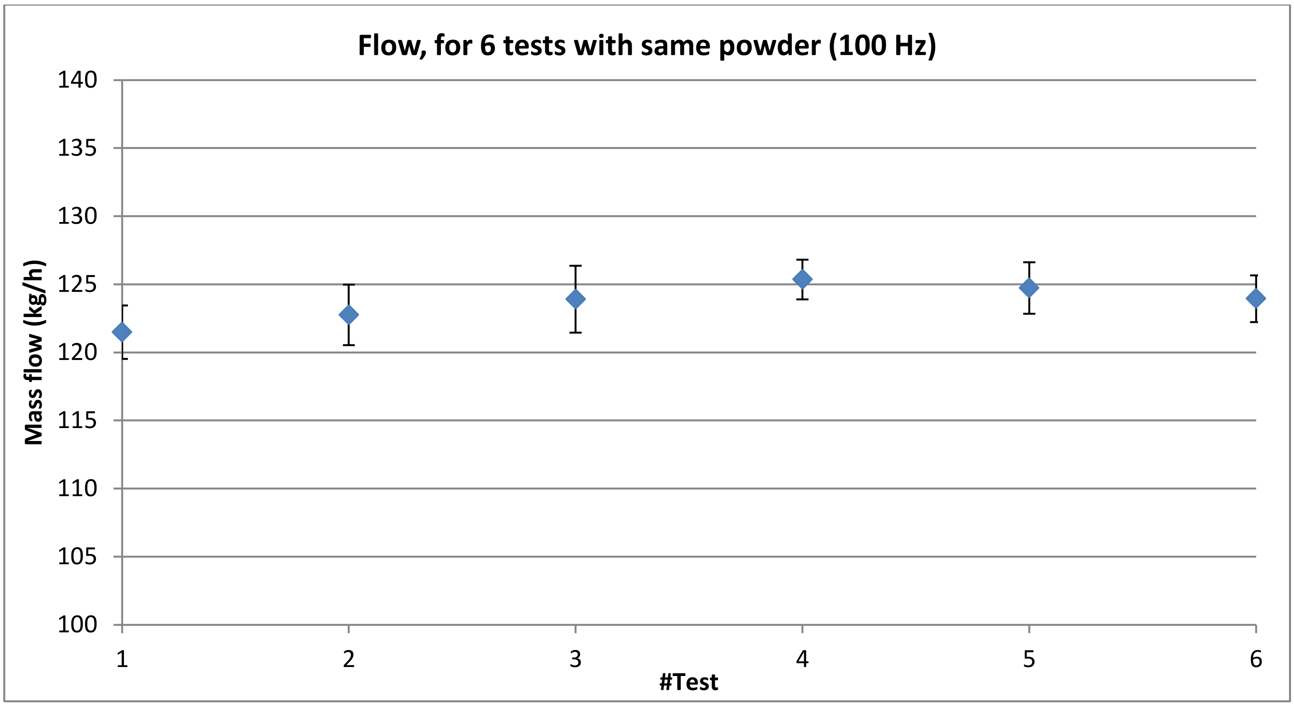


Figure 9 Graph of the evolution of mass flow between 6 tests with the same powder at 100 Hz

This graph shows that there is not a significant effect of the number of tests on the mass flow.

The variation between the lowest flow and the highest flow is about 3%. This difference is smaller than the standard deviation.

It means that the feeding system does not modify the powder properties (i.e. the density).

3.3.3. Experiment #2 – Variations between several tests

The goal of the second experiment is to see the flow variations between 2 experiments, and also to compare with the value of variations with the first experiment.

This experiment consists of the same 6 experiments but with new powder each time.

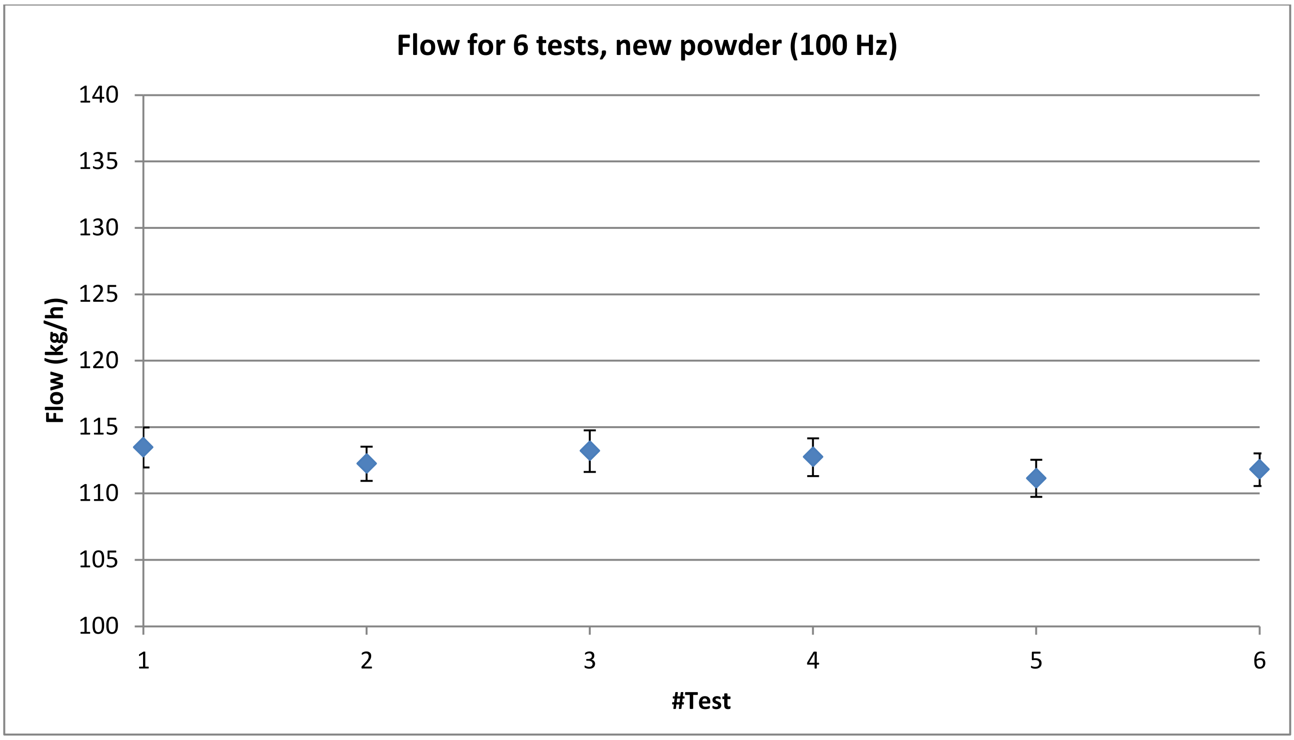


Figure 10 Graph of the evolution of mass flow between 6 tests with new powder each time at 100 Hz

The difference between the lowest and the highest mass flow is lower than 3%, similar to the standard deviation value.

The variations are the same than for the first experiment.

We can conclude that for a fixed speed of the screw, the variation of the flow is very low between different experiments.

Note: the difference of the flow value between experiments #1 (~123 kg/h) and #2 (~112 kg/h) can be explained by the experiment #5 (cf. page 12) which shows that the flow depends on the level of powder in the tank. The experiment #1 and #2 have not been done with the same level of powder in the tank.

3.3.4. Experiment #3 – Evolution of the flow in function of the frequency

The following test has been done to characterize the evolution of the flow in function of the supply frequency of the screw motor. The aim of this study is to know the flow range.

The graph below shows the mass flow for 6 different supply frequencies (10, 25, 40, 55 and 70 Hz).

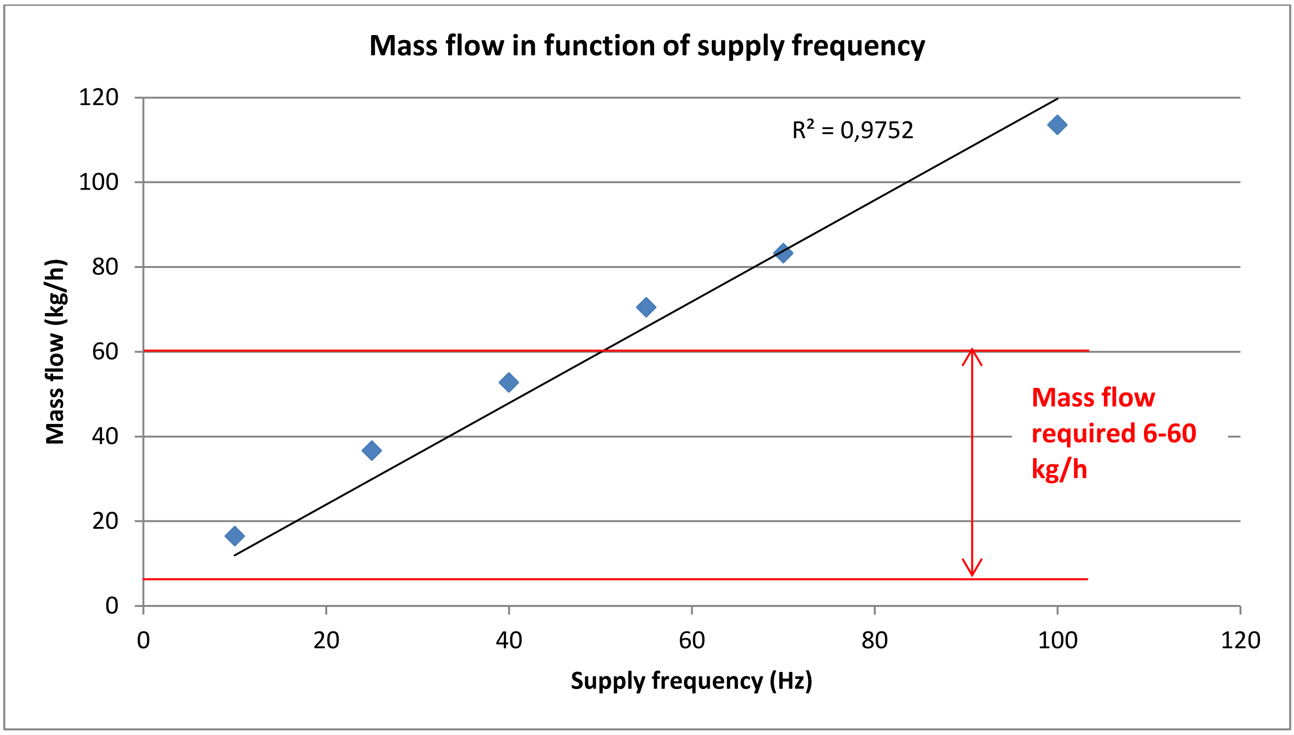


Figure 11 Graph of the evolution of mass flow vs. supply frequency

This experiment shows two important points:

First, the evolution of the mass flow is linear in function of the frequency within range that has been examined. It means that the filling rate of the screw does not change when the screw speed increases

As mentioned in the “function tests” part, it confirms that the bridge breaker is very efficient.

The second point is that we cannot feed under 15 kg/h, although the minimum mass flow required is 6 kg/h. This is due to the gear motor used on this prototype, which has a synchronous speed (at 50Hz) of 34 rev/min.

To resolve this problem and to respect the flow range required by the CEA, a slower motor will be provided on the final version of the feeding system.

The following graph introduces the volumetric flow in function of the supply frequency of the screw motor. This graph is made on the hypothesis that the density of the powder is 220 kg/m^3.

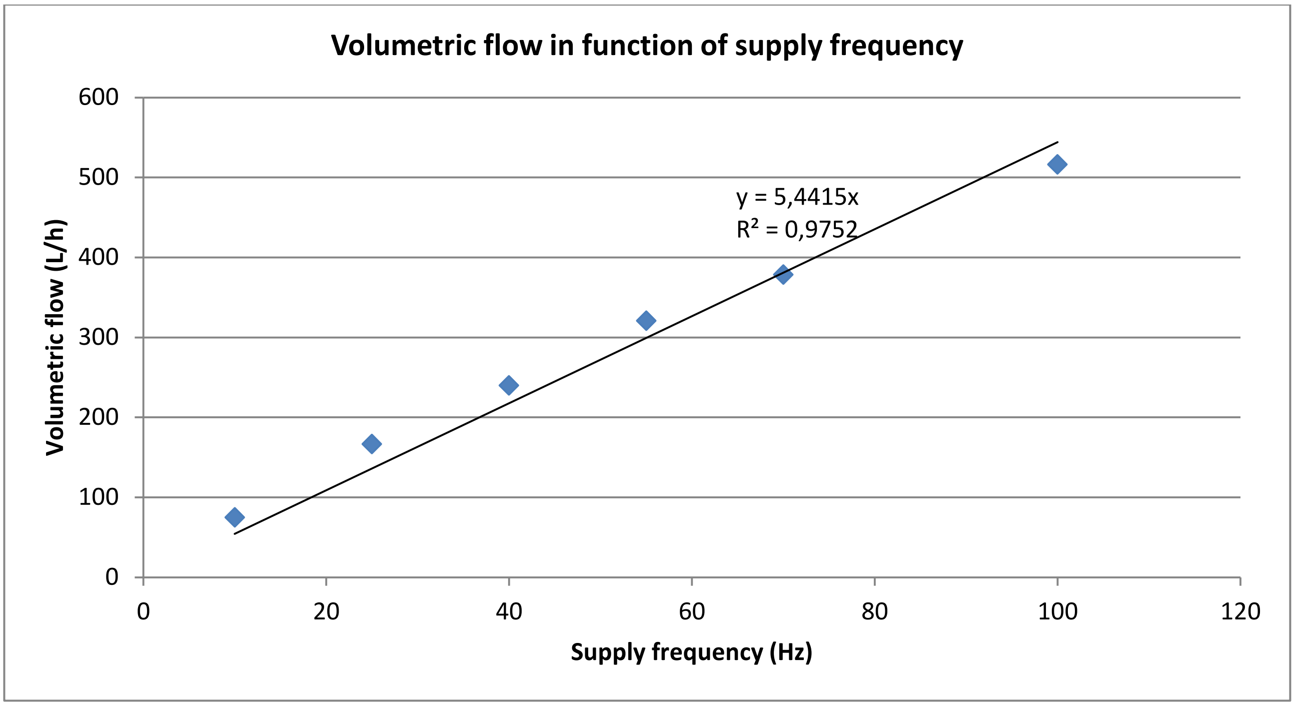


Figure 12 Graph of the evolution of volumetric flow vs. supply frequency

Based on the motor put on the system delivered to CEA, an estimate of the volume flow is the volumetric flow shown in figure 11 times the ratio between the two motor velocities.

3.3.5. Experiment #4 – Fluctuation of the flow during a test

Thanks to these experiments, it is also interesting to focus on the flow fluctuation during an experiment. The CEA specification is a maximum of 5% of fluctuation of the flow during the operation.

A test at 70 Hz is taken in example. The next graph introduces the evolution of the flow during the experiment on the next graph.

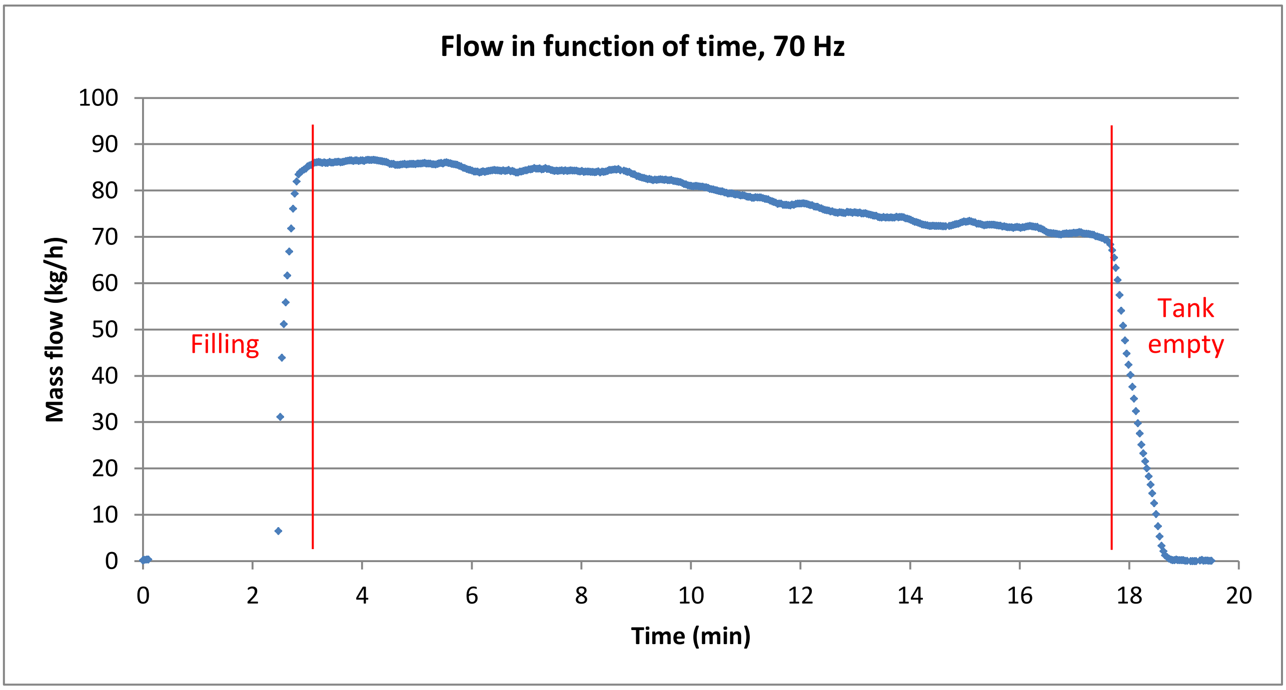


Figure 13 Graph of the evolution of mass flow vs. time at 70 Hz

We can see on this graph that the mass flow decreases in function of the time. In a first time, the flow is almost constant during 5 minutes and then starts to decrease.

The difference between the lowest and the highest flow during this experiment is about 19%.

We can find the same evolution of the flow for other frequencies tests. We noted that the flow starts to decrease at the same time, corresponding to a weight of 10 kg of wood powder in the tank.

The volumetric flow is expected to be constant. So the hypothesis is that the mass flow fluctuation is due to the variation of the wood powder density.

According to the powder F315 specifications, the density is very variable depending on the compression rate.

At the beginning, when the tank is full filled, the compression of the powder increases the density of the powder which is in the bottom of the tank, resulting in a high mass flow. When the tank is almost empty, the powder is not compressed and has a lower density, resulting in a lower mass flow.

3.3.6. Experiment #5 – Confirmation of the hypothesis

In order to check and confirm this hypothesis, two last experiments have been done.

To avoid this fluctuation of the wood powder density, a test by filling the tank frequently has been done. A frequent filling permits to maintain the same level of powder in the tank, resulting in a constant compression rate of the powder in the bottom of the tank.

The following graph shows the results, at the same frequency (70 Hz) than the previous test. The mass flow is in blue and the mass of powder in red.

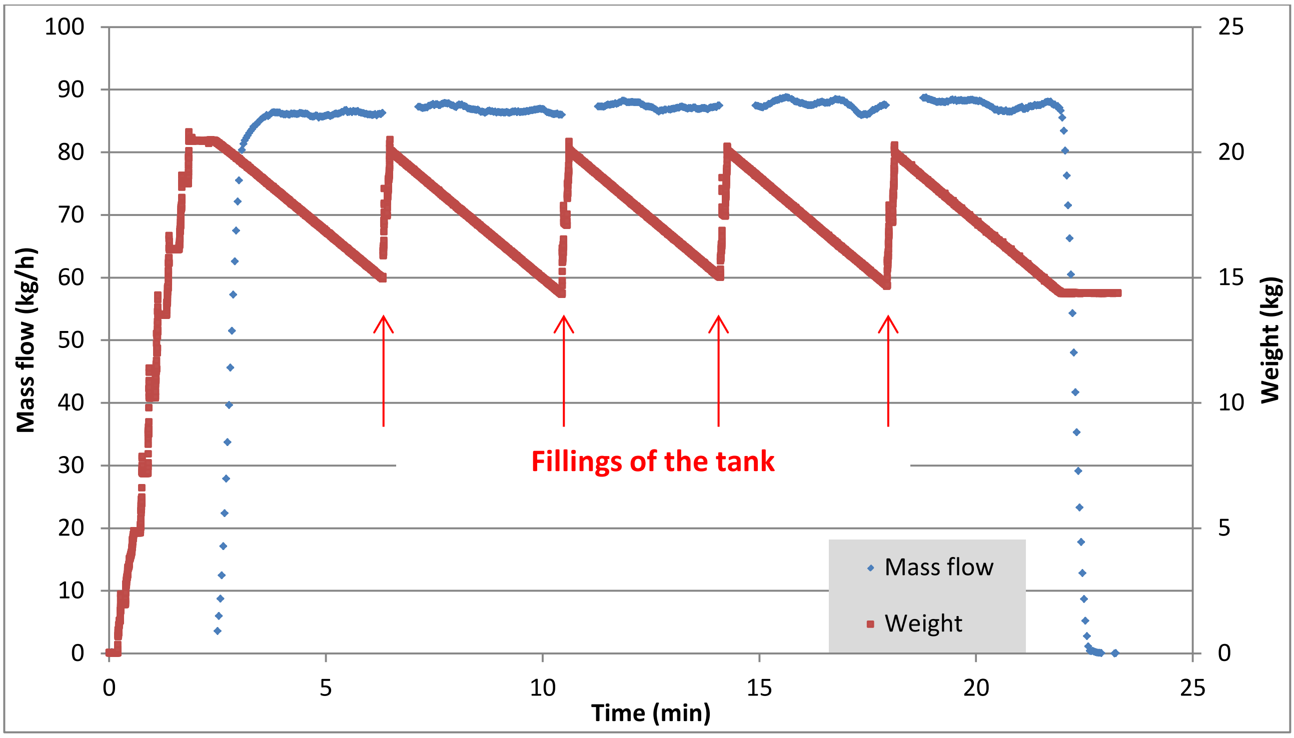


Figure 14 Graph of mass flow and weight of the system vs. time at 70 Hz

This graph shows that the mass flow has a lower fluctuation than for the previous experiment. Indeed, the variation between the lowest mass flow and the highest mass flow is about 3.5%. This value confirms our hypothesis that the powder level in the tank modifies the flow.

Another test has been done, also at 70 Hz, with an incompressible powder (constant density) and without filling the tank during the experiment. The evolution of the mass flow during the test is shown on the following graph.

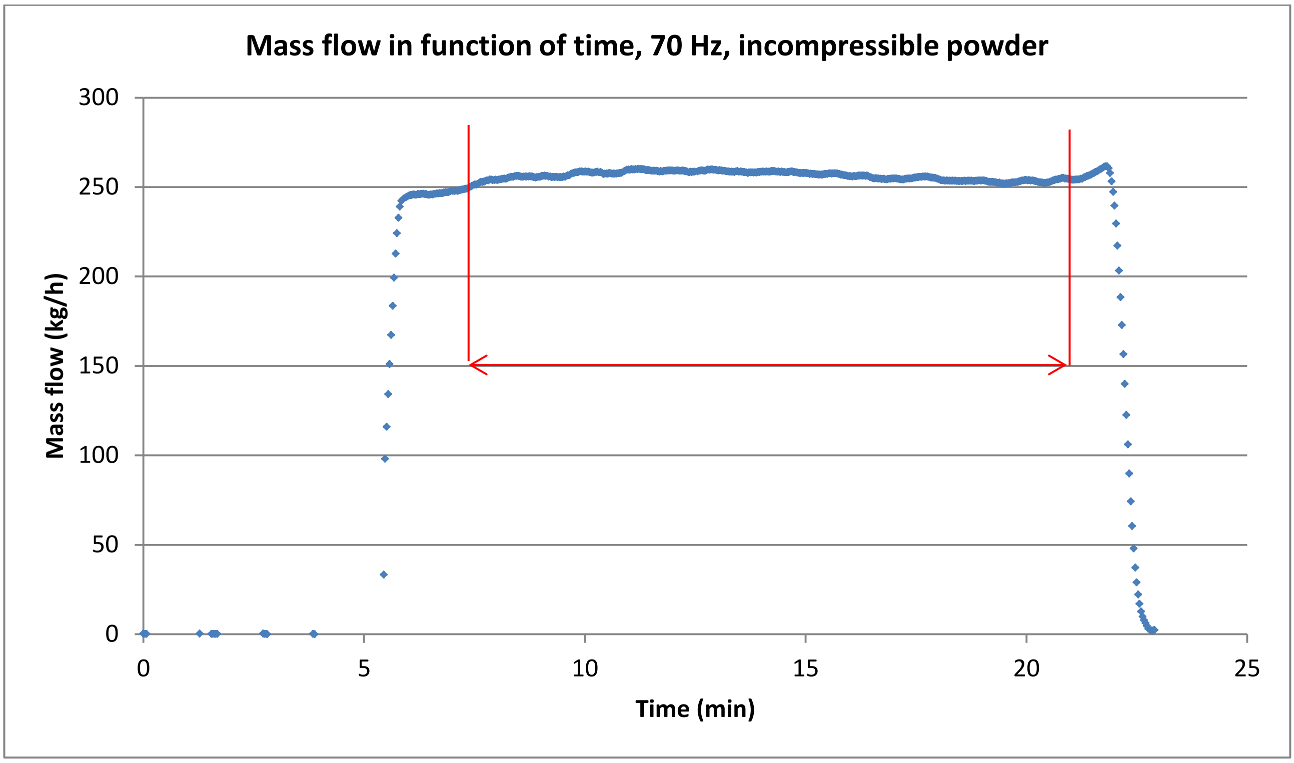


Figure 15 Graph of mass flow vs. time with incompressible powder at 70 Hz

The mass flow is higher than the previous values because the powder used for this test has a higher density (0.6 kg/L).

The maximal fluctuation of the mass flow during this test is about 3.1% without filling the tank. This value adds another checking of the hypothesis.

3.3.7. Operating conditions

This feeding system is designed for a continuous operation and is more efficient with a continuous filling of the tank.

In the case of a compressible material to feed, TK Energy has determined a low level limit in the tank: this low limit is 40 cm below the top of the tank.

If the level of powder is above than this low level, TK Energy guarantee that the flow fluctuation is lower than 5% during the operation.

If the feeding system works below this low limit, the accuracy of the flow will decrease if the powder can be compressed by its own weight.

3.4. Conclusion

TK Energy has developed an accurate feeding system of wood powder. The development process has consisted in the design and manufacturing of a prototype, its testing and improvement, and the production of a final dosing bin able to deliver 100 kg/h of micrometric wood powder.

The system can dose this wood powder with variation lower than 5% of the flowrate and without formation of bridge of material inside the bin. The dosing bin has endured experiments with both compressible and non-compressible wood powder.

4. **Atmospheric fuel preparation and dosing**

In this part is presented the development of an atmospheric fuel preparation and dosing facility.

4.1. Description of the project

The scope of the initial project is described hereunder.

The initial scope of the project was to demonstrate a flexible energy production from low quality biomass at high energy efficiency and high energy flexibility. The state of the art of commercial gasification of biomass is the coal gasifier, where coal and biomass is co-fired. In that case, the particle size of the biomass has to be less than 0.2 mm, because of the short residence time in the gasifier. This can lead to a major cost for fuels, as it requires extensive pre-treatment. Furthermore, a number of gasification plants are operating at an economical loss but are being maintained in operation as R&D or demonstration plants. These plants are either very complex e.g. plasma gasifiers or simple gasifiers that face tar problems e.g. fluid beds. In contrast to the above technologies the innovative idea in this project is to demonstrate an entrained flow gasification reactor, which is significantly less sensitive to particle kinetics, does not produce tars and produce a completely vitrified slag.

In PSO project no. 4781 “Højtemperatur slaggende affaldsforgasser” a new gasification technology with a capacity of 1 MWth was proven with wheat flour and sewage sludge as fuels. The main component developed in the project was a cyclonic gasification chamber with a mechanopneumatic fuel dosing system, where the fuel was mixed with oxygen enriched air before being blown tangentially into the gasification chamber. It was shown that it was possible to increase the residence time of the particles with orders of magnitude. This reduces the requirements for particle size and thereby the requirement for pre-treatment. It was also shown that the slag is stable towards leaching of heavy metals and therefore can be recycled e.g. as building material.

In the French-Danish project SLUGAS, funded by ANR and TK Energy where CEA, CNRS, Suez and TK Energy participated, the behaviour and fate of inorganic compounds in sludge gasification was investigated. An improved ceramic wall material was identified and a model for lifetime predictions and heat losses for cooled and insulated gasification chambers was established. The present project continues the former work by up scaling to 10 MWth. Demonstration in this size secures that the “real full size challenges” will be observed. It is expected that the major market for gasifiers will be from 50 MWth and above, therefore the technical solutions will be targeted against technology relevant for further upscaling. The gasification chamber with fuel and oxidant inlet is assessed to be the critical component and a work package is therefore dedicated for this upscaling. The upscaling will include experiments with two open gasification chambers at 3 MWth and 10 MWth where the fuel and oxidant inlet can be optimized and the capacity can be verified. The up-scaled gasification chamber will be included in a complete gasification plant. The gas will in the initial experiments be flared, followed by utilizing of a slip stream of the gas for electricity production with a gas engine. The technology will be demonstrated for 500 hours, using two types of low quality biomass as fuel; garden and park residues and sewage sludge. The research part of the project will focus on ash/slag behaviour, where evaporation, melting and viscosity phenomena will be studied. The understanding of these parameters is necessary to be able to control and regulate the gasification process, in order for the ash/slag to be completely melted and having the viscosity necessary to both cover the whole surface of the gasification chamber and also to be able to run out of the gasification chamber. Furthermore, the life time of the gasification chamber will, beside erosion, depend on the ceramic corrosion of the wall by the liquid slag. Therefore a new developed wall design will be tested, that is targeted against biomass slag. The project has chosen low quality biomass as fuel because it improves the business case and thereby makes the market penetration easier. The technology is also relevant for higher quality biomasses e.g. wood or straw, but as no renewable energy sources can be neglected in the future fossil free society, it is prioritized to focus on low quality biomass, which cannot be utilized in existing commercial energy technology. The project defines low quality biomass as biomass with high water content, contaminated by heavy metals or fibrous texture making it difficult to utilize using conventional technologies. Beside these properties the biomass types are characterized by no superior utilizations methods and being available in reasonable large amounts. An example is the garden and park residues, where 600,000 tons/year, (12 PJ = 1.5 % of the total Danish primary energy consumption) today is converted to compost using energy and having a high CO2 impact. The business plan is, as part of the project, improved with a study of potential fuel types and an evaluation of the position of the technology in the Danish energy society. The two potential end users that are partners in the project will contribute to making these analyses as market relevant as possible. This upscaling project bridges the gap from small proof of concept to long term demonstration. The next phase will be a demonstration plant that will be operated for at least 10,000 hours in order to prove the technology. The subsequent sales strategy is to find an experienced commercial partner having a strong global network. The commercialization process of the technology will in the present project be started using local stakeholders.

The following results were expected from the project:

- Upscaling the technology to 10 MWth
- Demonstration of slagging entrained flow gasification for a total of 500 hours
- A technology that converts low quality biomass into an energy resource
- A business case that can convince a local stakeholder to participate in a demonstration project.

4.2. Global process

4.2.1. Description

The FLOWGAS project aims to develop an atmospheric gasification process for converting low quality biomass into energy (electricity, heat).

The project was defined in two phases. First, the development of the fuel supply line and a 3 MWth gasifier. Then, based on the results of the first phase, the development of a 8 MWth gasifier and the post-treatment process associated. Hereunder is described the principle of this process.

The low quality fuel is loaded into the intake container. This container has the function to store but also dry the fuel material, by injection of hot air through. The material goes then through a stone removal system and falls into a feeding bin. This component feeds a downsizer with fuel material. The downsizer has the double function of downsizing and transporting the material into a dosing unit.

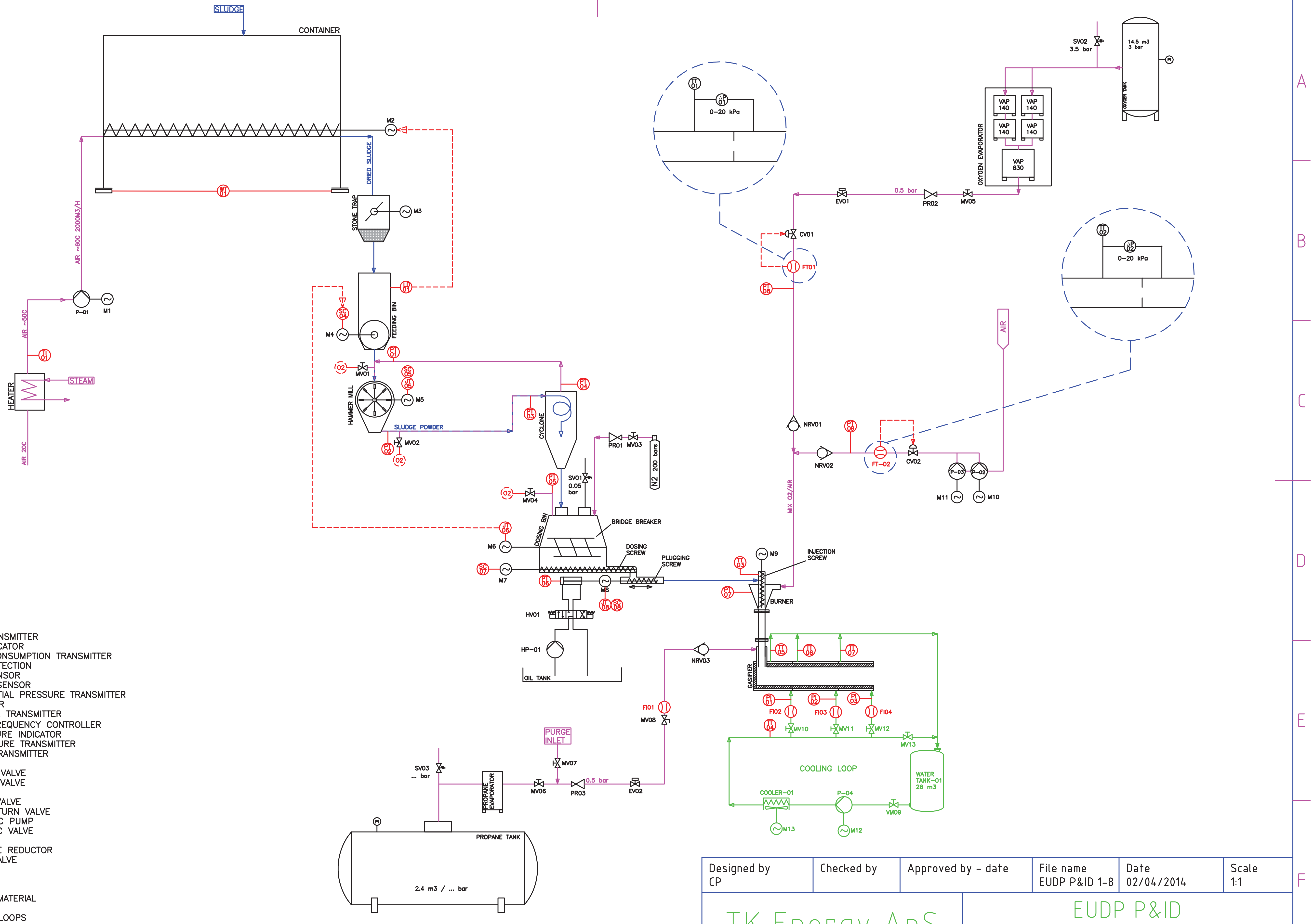
There, the fuel material is fed at a selected and accurate flow towards the gasifier. In between, a plugging system isolates the dosing unit from the gasifier and prevents the dosing accuracy from being disturbed. Also, an injection system injects fuel material and oxygen into the gasifier.

The gasifier, an entrained flow reactor, operates at high temperature (around 1500°C) and atmospheric pressure. With addition of oxygen, it converts the carbon, hydrogen and oxygen elements contained in the biomass into CO, H_2, CO_2 and H_2O. The inorganics present in the fuel material turn into a slag or evacuated with the outlet gas if volatile.

A slag recovery system is placed after the gasifier. It catches, cools the slag coming from the gasifier and evacuates it from the process.
The gas is going through a water scrubber where it is cleaned and cooled. Then, the gas is send either into a 100 kW engine for conversion into electricity or to a flare where it is directly burnt.

4.2.2. P&ID

The two following P&I Diagrams show the 3 MWth demonstration plant and the up-scaled and more complete 8 MWth demonstration plant.



FT --> FLOW TRANSMITTER
FI --> FLOW INDICATOR
JT --> POWER CONSUMPTION TRANSMITTER
LD --> LEVEL DETECTION
LS --> LEVEL SENSOR
O2 --> OXYGEN SENSOR
ΔP --> DIFFERENTIAL PRESSURE TRANSMITTER
PI --> MANOMETER
PT --> PRESSURE TRANSMITTER
SC --> SPEED/FREQUENCY CONTROLLER
TI --> TEMPERATURE INDICATOR
TT --> TEMPERATURE TRANSMITTER
WT --> WEIGHT TRANSMITTER

CV --> CONTROL VALVE
EV --> ELECTRIC VALVE
M --> MOTOR
MV --> MANUAL VALVE
NRV --> NON RETURN VALVE
HP --> HYDRAULIC PUMP
HV --> HYDRAULIC VALVE
P --> PUMP
PR --> PRESSURE REDUCTOR
SV --> SAFETY VALVE

COLORS

BLUE --> SOLID MATERIAL
MAGENTA --> GAS
GREEN --> SIDE LOOPS
RED --> INSTRUMENTATION

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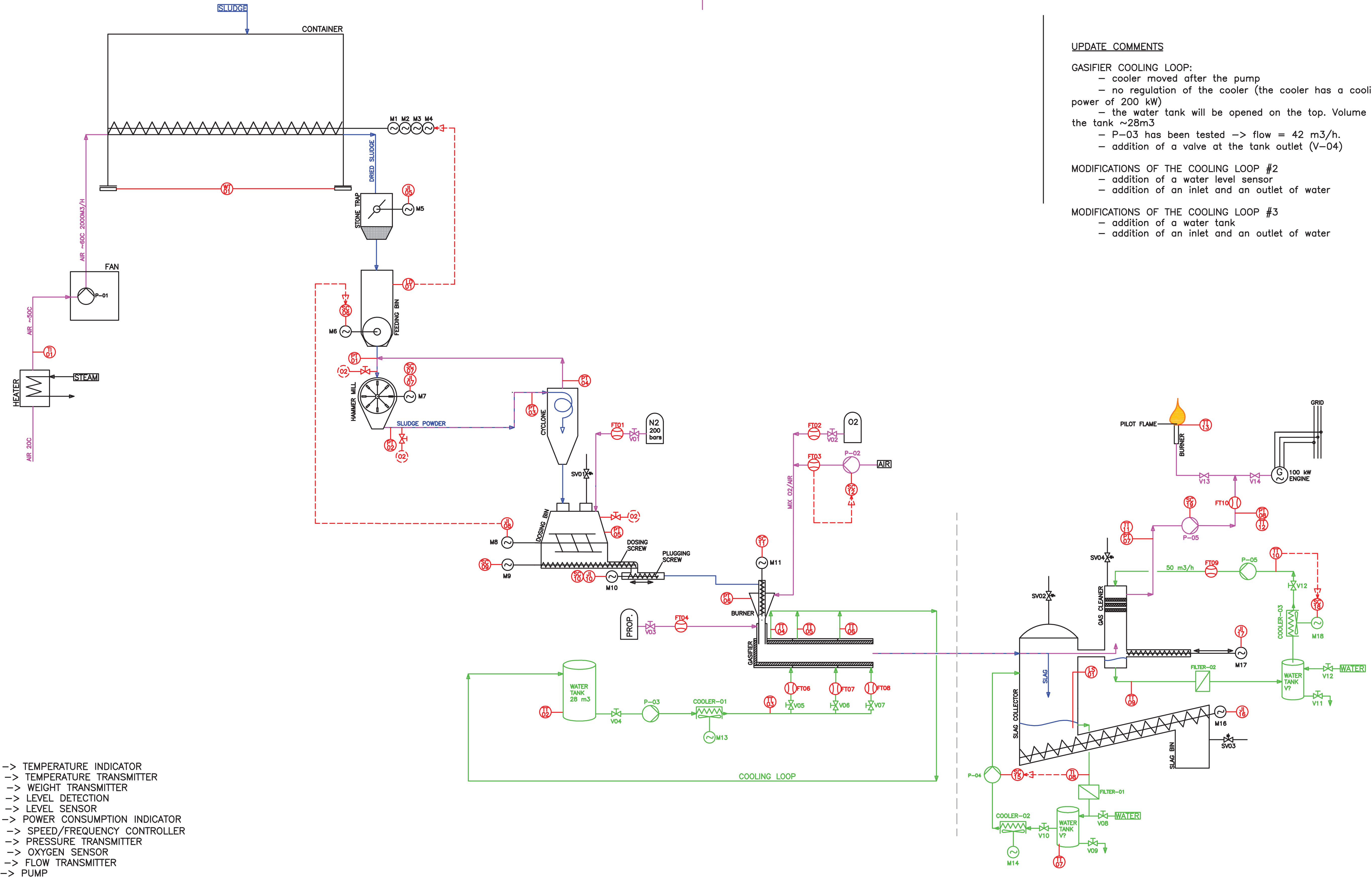

UPDATE COMMENTS

GASIFIER COOLING LOOP:
- cooler moved after the pump
- no regulation of the cooler (the cooler has a cooling power of 200 kW)
- the water tank will be opened on the top. Volume of the tank ~28m3
- P–03 has been tested –> flow = 42 m3/h.
- addition of a valve at the tank outlet (V–04)

MODIFICATIONS OF THE COOLING LOOP #2
- addition of a water level sensor
- addition of an inlet and an outlet of water

MODIFICATIONS OF THE COOLING LOOP #3
- addition of a water tank
- addition of an inlet and an outlet of water

TI –> TEMPERATURE INDICATOR
TT –> TEMPERATURE TRANSMITTER
WT –> WEIGHT TRANSMITTER
LD –> LEVEL DETECTION
LS –> LEVEL SENSOR
JI –> POWER CONSUMPTION INDICATOR
SC –> SPEED/FREQUENCY CONTROLLER
PT –> PRESSURE TRANSMITTER
O2 –> OXYGEN SENSOR
FT –> FLOW TRANSMITTER
P –> PUMP
V –> VALVE
SV –> SAFETY VALVE

COLORS

BLUE –> SOLID MATERIAL
MAGENTA –> GAS
GREEN –> SIDE LOOPS
RED –> INSTRUMENTATION

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4.2.3. List of the main components

Component	Function
Drying container	Storage and drying of fuel material
Stone trap	Removing unwanted materials from the fuel and breaking fuel material clumps
Feeding bin	Feeding the process with fuel material
Hammer mill	Downsizing of fuel material into thin powder
Cyclone	Separate the downsized fuel material from the air flow
Dosing bin	Dosing fuel material with an accurate and stable flow
Plug screw	Sealing against pressure fluctuations and preventing of backflow
Burner	Injection of fuel material and oxygen/air into the gasification chamber
Air supply	Supplying of air to the gasifier
Oxygen supply	Supplying of oxygen to the gasifier
Propane supply	Supplying of propane for starting up the gasifier
Gasifier	Conversion of the fuel material into synthesis gas
Cooling system	Control of the gasifier temperature
Slag collector	Recovery and cooling of hot slag
Cleaning screw	Removal of solid residues from the pipe between slag collector and water scrubber
Water scrubber	Cleaning and cooling the gas
Flare	Burning the gas produced
Engine	Production of electricity from the gas produced

Figure 18 Table of the main process components

4.2.4. Overall drawing

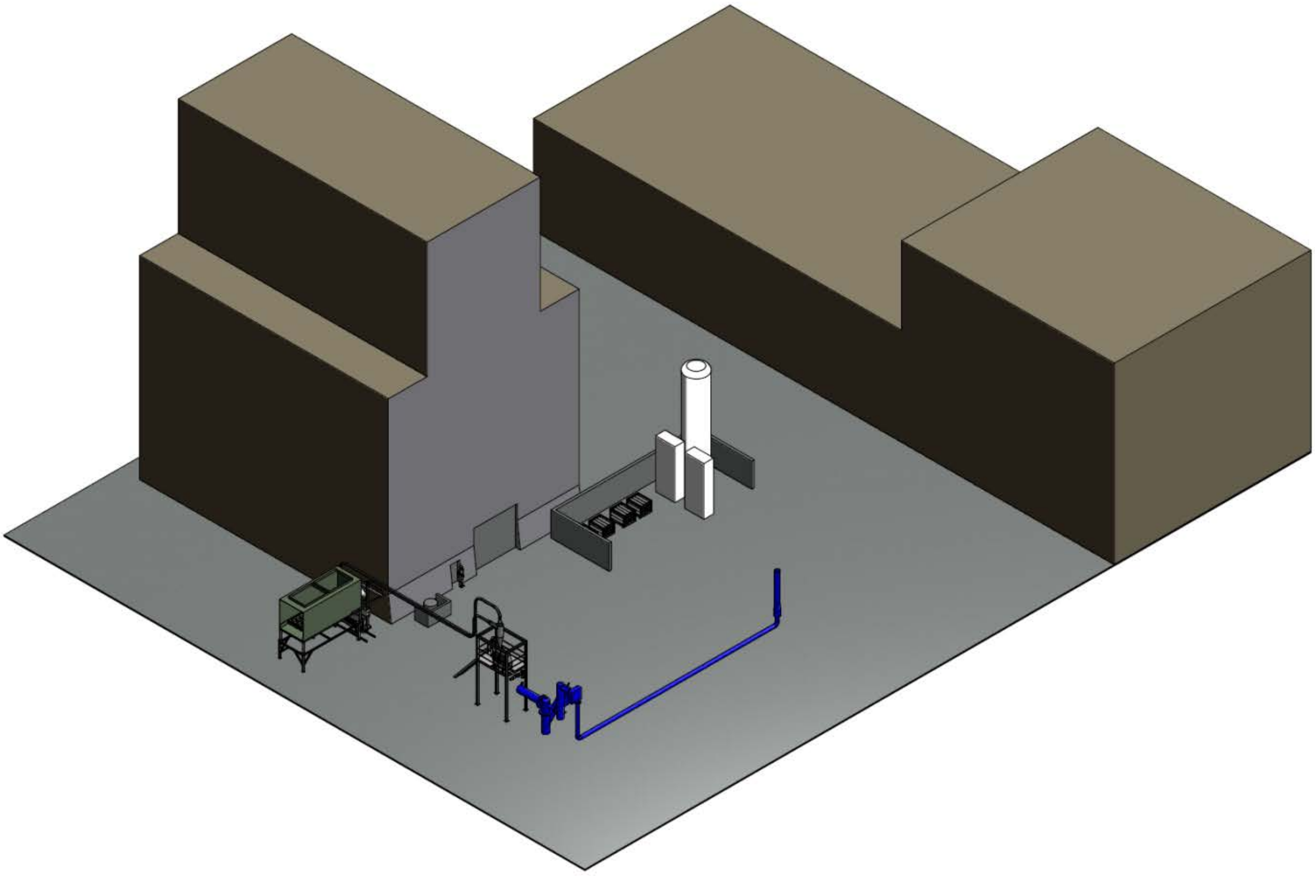


Figure 19 Overall sketch of the demonstration facility

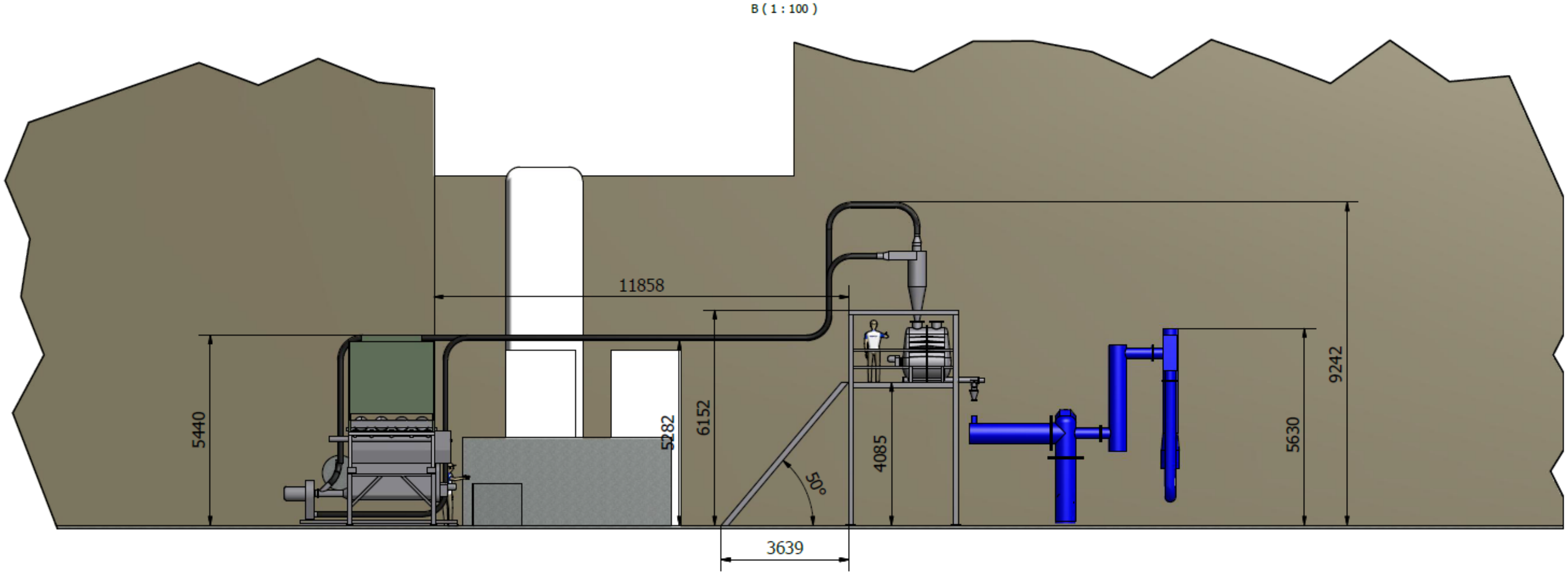


Figure 20 Sketch of the demonstration facility

4.3. Demonstration facility

In this part are described the different parts of the demonstration facility that has been developed and tested on TK Energy’s site. The steps match with diagram n°1.

4.3.1. Pre-treatment

The pre-treatment of the biomass was not included in the scope of this project. However, the biomass cannot be handled raw by the demonstration facility. A simple and cost effective pre-treatment system has therefore been built in order for the demonstration process to be able to handle the fuel material.

It consists of an atmospheric air dryer coupled with a stone removal system.

4.3.1.1. Dryer

Figure 21 Picture of the drying container

The dryer has been built from a 15 m^3 container with a large opening on the top. The container can be loaded with a truck loader. Fuel material is removed from the container after drying by 4 screws (Ø400 mm / pitch 400 mm) and placed at the bottom of the container. Each screw shaft (ø89 mm) is equipped with a gear wheel. The 4 gear wheels are driven by a hydraulic piston resulting in the rotation of the screws and removal of the dry material from the dryer.

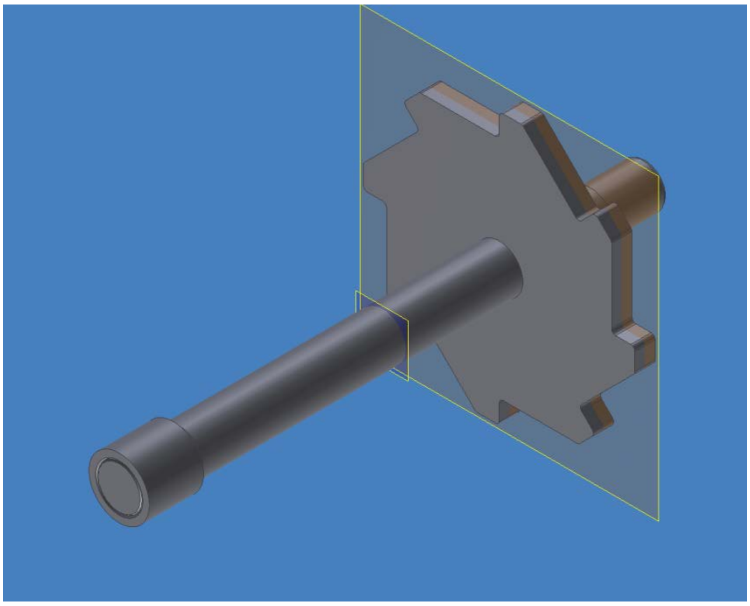


Figure 22 Sketch of the gearwheel for container screws driving

Below the screws, on the bottom of the container are welded 6 triangular drying channels. The screws are placed in between the drying channels. The drying channels have some openings allowing air to blow through the material. The air channels are supplied with hot air at a temperature of 60°C. Air is heated by a steam exchanger and then blown by a 9 kW blower with a capacity of 2000 m3/h.

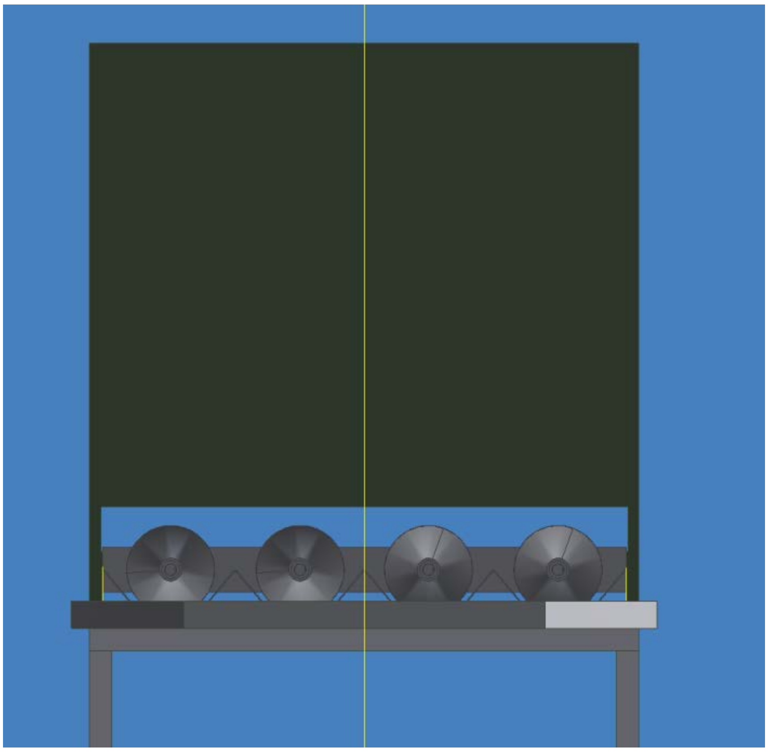


Figure 23 Sketch of the drying container with the screws and drying channels

Figure 24 Picture of the blower supplying air to the dryer

The dryer is mounted on 4 load cells of 5 tons allowing a measurement up to 20 tons. The signal from the load cells is amplified and sent to a control computer. With this measurement, the mass of water evaporated by the drying can be monitored. By crossing with the initial moisture content, the final moisture content can be deduced. The flow of material which is taken out of the dryer by the screws can also be monitored.

At the outlet of the dryer is placed the stone removal unit, with has a buffer volume. The stone removal unit is equipped with a level sensor. When full, the dryer screws are stopped and are activated when the level decreases again.

4.3.1.2. Stone removal system

At the outlet of the dryer is located a stone removal system. During drying, some quantities of the fuel material can agglomerate together and form hard lumps (i.e. with sewage sludge). The function of the stone removal system is catching foreign material present in the fuel, stones for example, without removing fuel material.

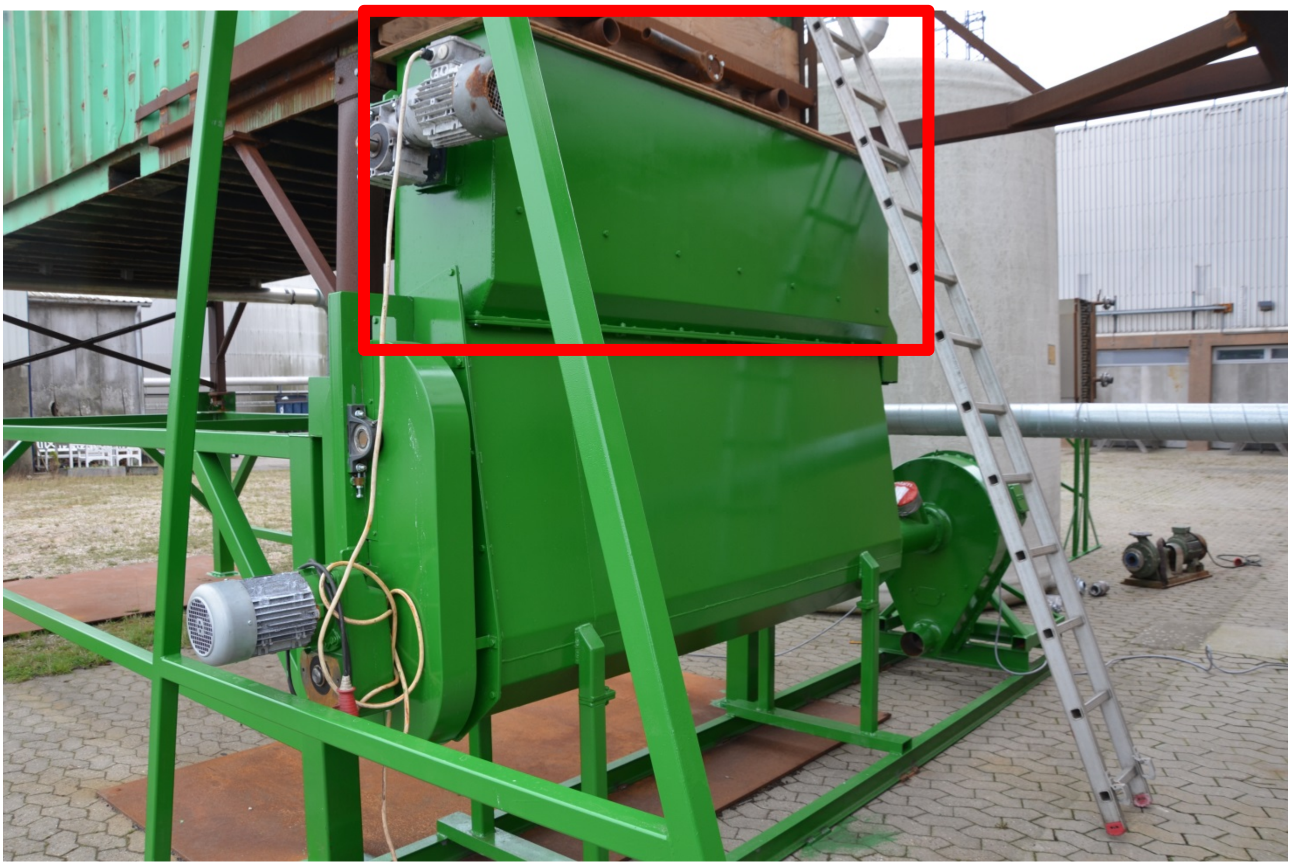


Figure 25 Picture of the stone removal system

The development of the stone removal unit has been through a prototype test campaign where different designs have been tested. An efficient prototype has been up-scaled and can handle several tons of material per hour. The principle uses rotating chains breaking down the lumps of material at a speed of 300 rpm and is driven by a 3 kW motor.

A grid positioned at the bottom of the stone removal system lets the material going through but catches all foreign material that is not downsized by the rotating chains. Stones or steel pieces get retained on top of the grid.

With the slope of the grid (5°) and the action of the chains, the stones and other foreign materials fall into a small recovery tank placed at the end of the grid. This tank is periodically emptied by manual operation. A manual emptying operation is suitable for this demonstration process where the stone trap does not need to be emptied frequently. However, an automatic emptying system could be easily built for an industrial scale process.

It has been decided to keep the stone removal system constantly running when the process is started, independently of the flow of material coming from the dryer. Starting and stopping phases can create vibrations and therefore a steady state operation is preferred.

Figure 26 Picture of the stone removal system during testing

4.3.2. Downsizing and pneumatic transport

After being dried and “cleaned” from foreign materials and stones, the material is now ready to be fed through the process.

The next steps are the downsizing of the biomass and its pneumatic transportation towards the dosing system. Downsizing and transportation is ensured by a feeding bin, a hammer mill and a pneumatic loop.

4.3.2.1. Feeding bin

The stone removal system is mounted on top of the feeding bin. In this configuration, the material falls directly into the feeding bin after having been through the stone removal system. The feeding bin consists of tank in which a screw is rotating at the bottom. By rotating, the screw takes the material from the feeding bin into the downsizer.

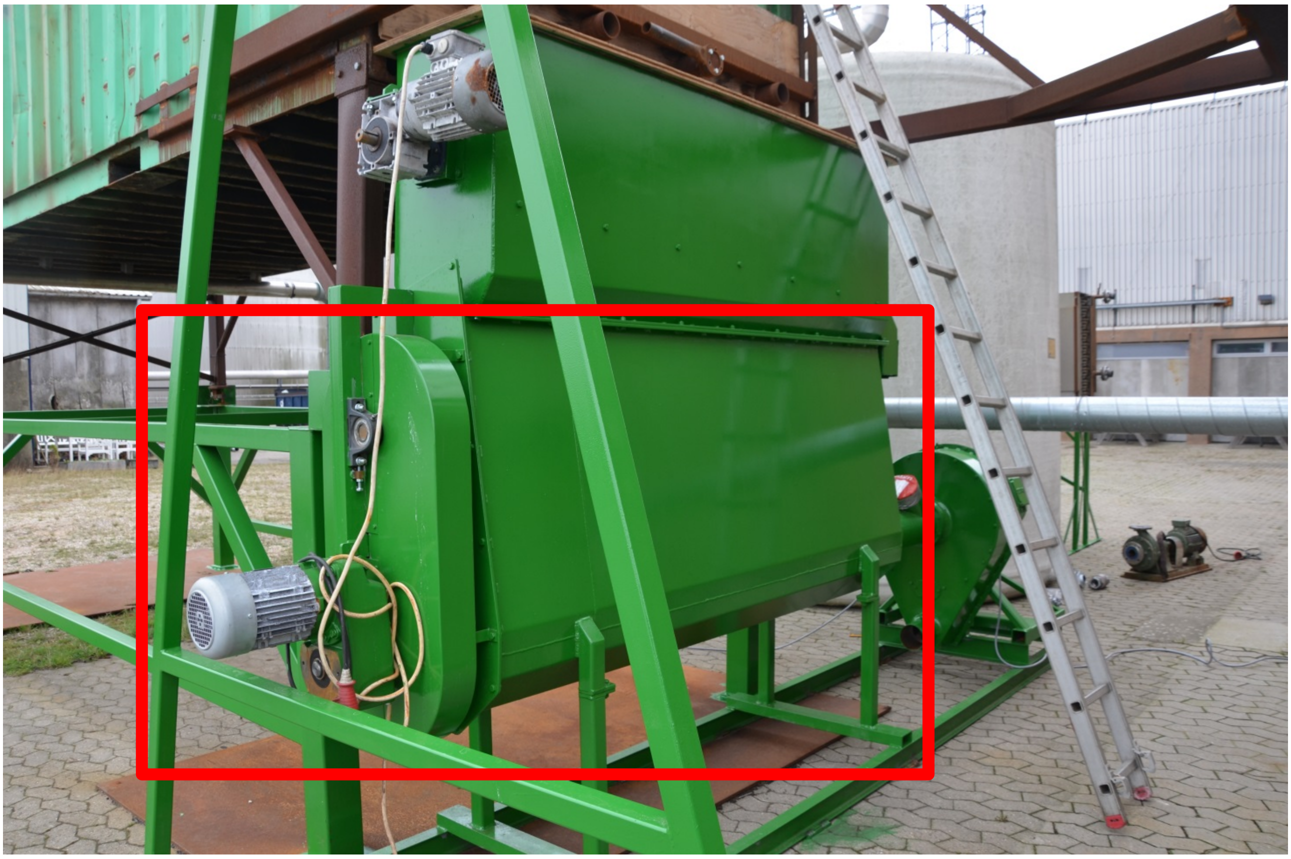


Figure 27 Picture of the feeding bin

The screw is made of two parts. The main screw with a diameter of 400 mm moves the material towards the outlet of the feeding bin. On the end, a second screw with a smaller diameter rotates at higher speed and injects the biomass through the Ø200 mm pipe. The flows of material are equivalent in both parts of the screw.

A gear system with a cogwheel and chains drives the two screws with only one motor (2.2 kW) and always the same speed ratio between the two screws. The transmission is ensured by a double shaft system: the outer and hollow shaft drives the bigger screw part; the shaft of the end screw is rotating in its centre. A ball bearing is mounted on each end for the mechanical connection between the two shafts.

The flow of material is controlled by a frequency controller from which the rotation speed of the motor can be changed. The feeding bin is equipped with a capacitive level sensor. When a high level in the feeding bin is detected, the inlet flow from the dryer is automatically stopped. When the level has decrease, material starts again to flow into the dosing bin.

The characteristic of material flow versus motor speed of the feeding bin is known from initial tests but is monitored by the mass evolution of the dryer and can then be adjusted during operation. For the first operations conducted with this demonstration process, the flow out of the feeding bin was adjusted during operation in order to keep a suitable level in the dosing bin. In an industrial process, the speed of the feeding bin screws would of course be automatically regulated by the level in the dosing bin.

4.3.2.2. Downsizer

Downsizing is insured by a hammer mill manufactured in-house. The hammer mill has a double function of downsizing and transportation. It crushes material into a thin powder and thanks to its fan effect blows it through a pipe to the dosing bin.

Figure 28 Picture of the hammer mill

The hammer mill is driven by a 37 kW motor. The rotation speed of the hammer is 2940 rpm. The material is fed in the centre and is discharged through the bottom. The movement of the hammers results in a fan effect that blows a high flow of air and downsized particles.

The first part of the downsizer is a disc equipped with 6 fixed hammers. It carries out a pre-crushing of the biomass by impact. Then, a thin downsizing is ensured between 4 other layers that have each 6 hammers on their periphery. These hammers are mounted on an axle but are free in rotation; in case of impact with a hard piece, the hammer can turn instead of getting bent.

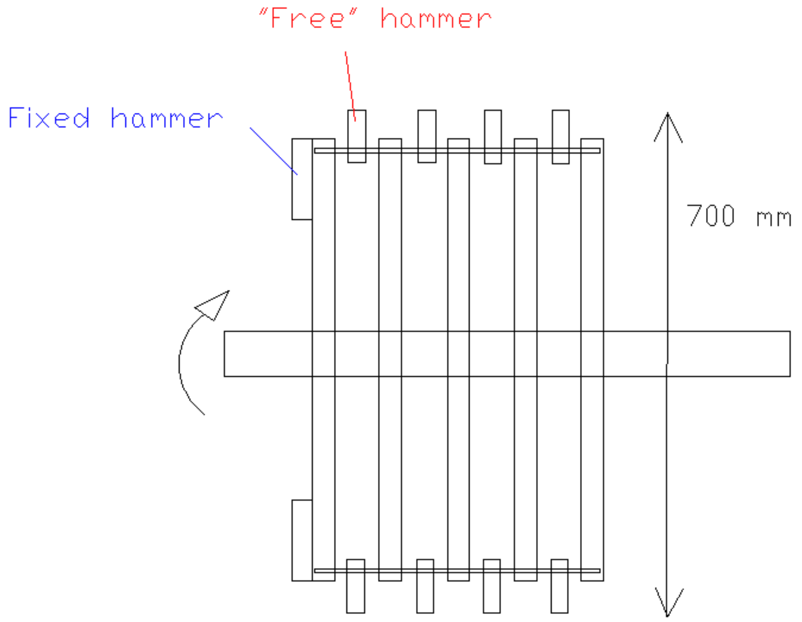


Figure 29 Sketch of the inner parts of the hammer mill

Below the hammers is placed a thin grid that let only thin particles going through the outlet of the downsizer.

4.3.2.3. Pneumatic transport loop

The hammer mill blows air and the crushed material through its outlet. The high flow of air moved by the hammer mill conveys the material towards the dosing bin, located about 15 meters from the hammer mill outlet.

Before falling into the dosing bin, the fuel material is separated from the air in a cyclone. The powder is falling down into the dosing bin while the air is evacuated through the top of the cyclone and goes back to the hammer mill through another pipe.

Figure 30 Picture of the cyclone on top of the dosing bin

The pneumatic loop is made of PVC pipes DN160. Bends of 90° with high bending length have been used in order to minimize the perturbations on the flow of air and powder. As they are not standard, these bends have been made in-house.
After few tests, a suitable procedure has been defined. A 16 straight piece of PVC pipe pre-heated in an oven at 125°C for 90 minutes. A special bending tool has been developed for this purpose.

The following pictures show the bending tool. After being heated, the end of the pipe is placed in the housing and the transversal beam is pulled. The roller, made of POM, shapes the pipe with the required angle without flattening it.

Figure 31 Pictures of the bending tool for PVC pipes

When bent, the pipes are locked by support brackets for preventing the bending angle to change. The different pieces of PVC pipe are carefully assembled and centred together with muffs before being fastened.

The pneumatic transport loop is monitored thanks to 4 pressure transmitters present along the loop and connected to the main PLC. The pressure transmitters are located at the inlet and outlet of the hammer mill and at the inlet and outlet of the cyclone.
These pressure measurements give the possibility to detect quickly a dysfunction in the transport loop. For instance, if a section starts getting clogged up with material, the pressure will quickly increase and the process can potentially be stopped.

4.3.3. Dosing

Dosing is an important step of the gasification process. The dosing unit has to provide a range of flow of fuel material. The flow has to be very constant in order to get stable conditions in the gasifier. The main difficulties are the mechanical properties of the fuel that can vary over time and the pressure fluctuations that can occur downstream in the gasifier.

TK Energy has developed a dosing bin meeting these requirements. A lot of the project resources have been used on this key component and a long experimental testing stage has been conducted before being set up with the rest of the demonstration process.

The design of the dosing bin is partly based on the first dosing bin technology described previously in this report.

Figure 32 Sketch of the dosing bin

The outer shell of the dosing bin has been made of two parts in order to be able to mount the internal mixer, also called “bridge breaker”. This rotating piece ensures a good filling of the dosing screw placed in the pipe at the bottom of the dosing bin. The bridge breaker is also used as a level measurement tool, by monitoring of its power consumption. There is indeed a good correlation between the power consumption and the level of powder present inside the bin.

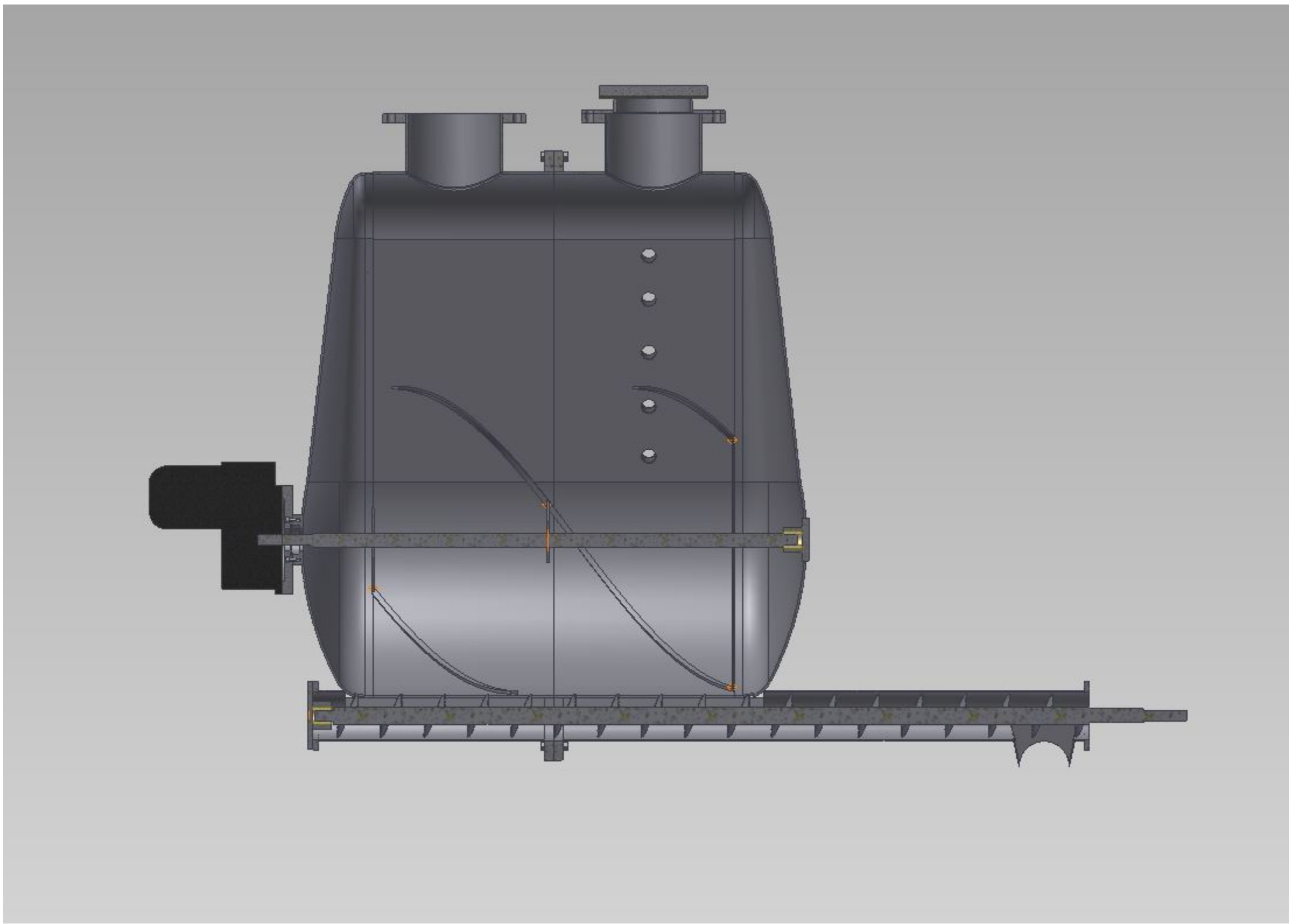


Figure 33 Cut view of the dosing bin

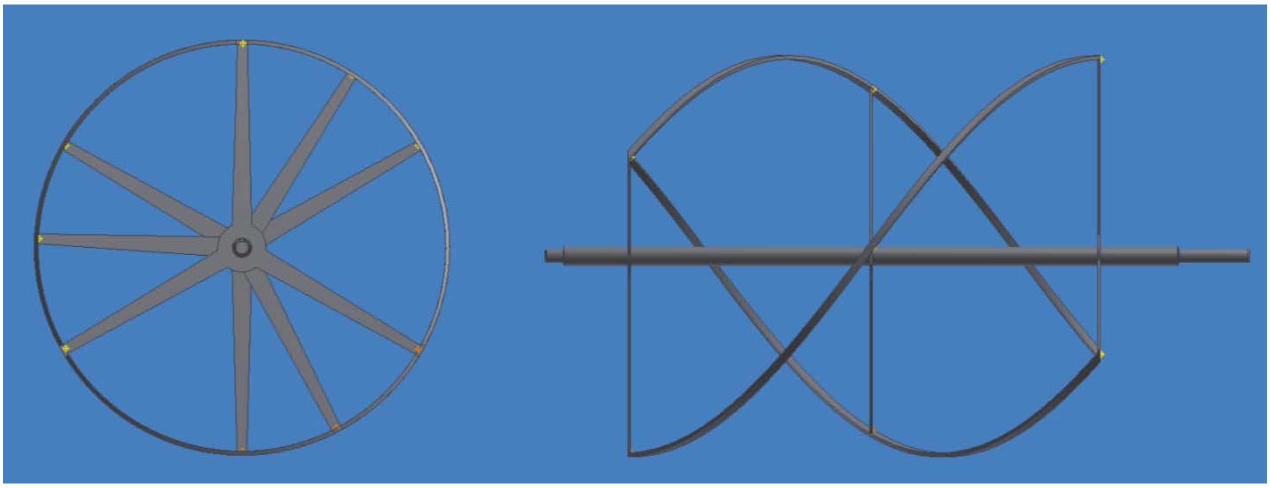


Figure 34 Sketch of the bridge breaker

Dosing screw specifications

Øshaft	30	mm
Øflights	94	mm
pitch	100	mm
Øpipe	132	mm
speed	18-180	rpm

The bin is equipped with 2 top flanges. The first one is dedicated to the inlet of fuel material whereas on the other one is mounted a safety valve set for 0.05 bar. In case of fire, the safety valve prevents from explosion of the dosing bin.

The dosing bin has 5 threaded sleeves giving the possibility of setting up instrumentation (level, oxygen or pressure sensors for example.

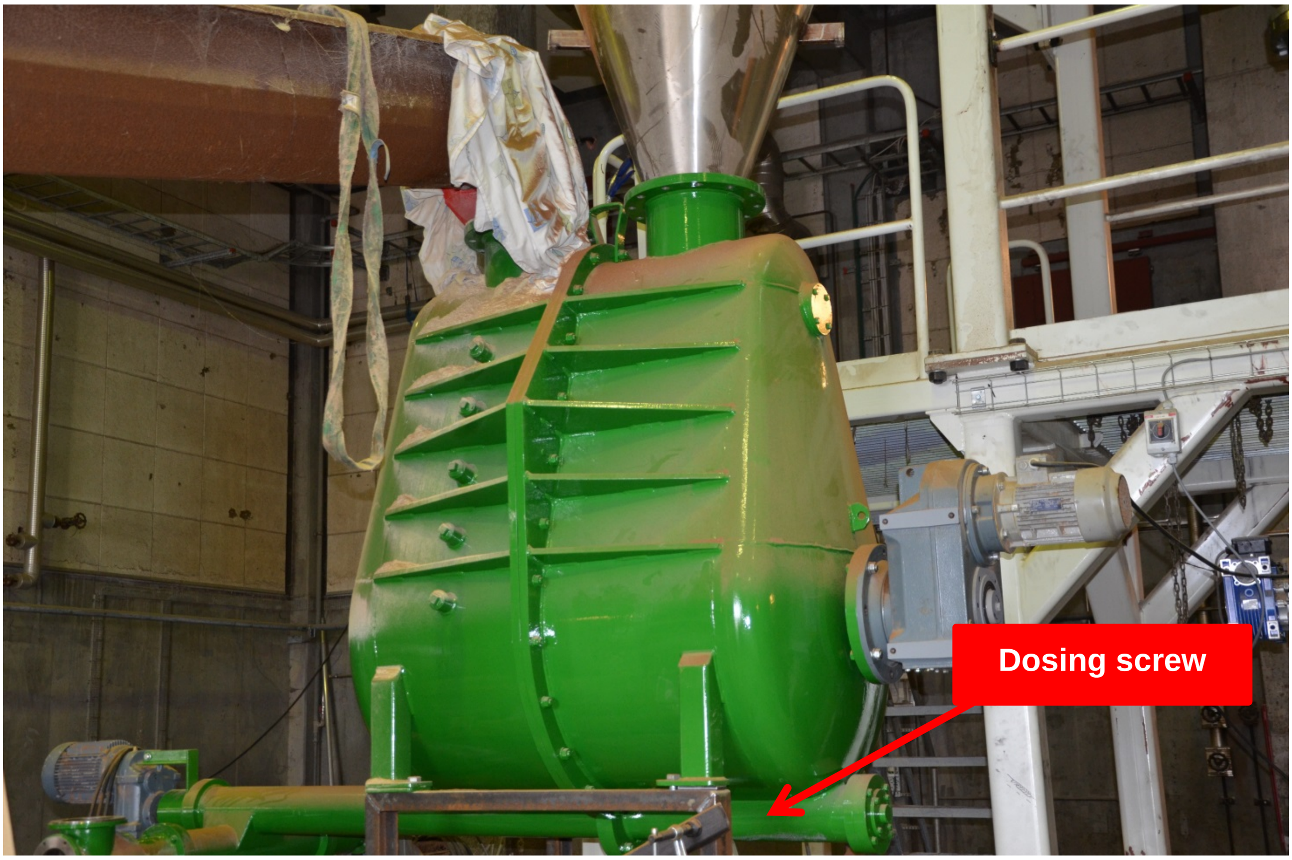


Figure 35 Picture of the dosing bin during testing phase

At the outlet of the dosing screw, the material falls into the plug screw which is placed perpendicularly.

During the gasification of material into the entrained flow reactor, the pressure in the gasifier can vary. These pressure variations can be due to several parameters (temperature, fuel feeding, slag production…).

A pressure fluctuation can disturb the fuel injection at the inlet of the reactor. This phenomenon could then amplify the pressure variation and result in instability of the gasification.

To avoid perturbation of the fuel injection, a plugging system has been developed. This plugging system is placed between the dosing screw and the injection screw and is designed to prevent gas flow between the gasifier and the dosing bin.

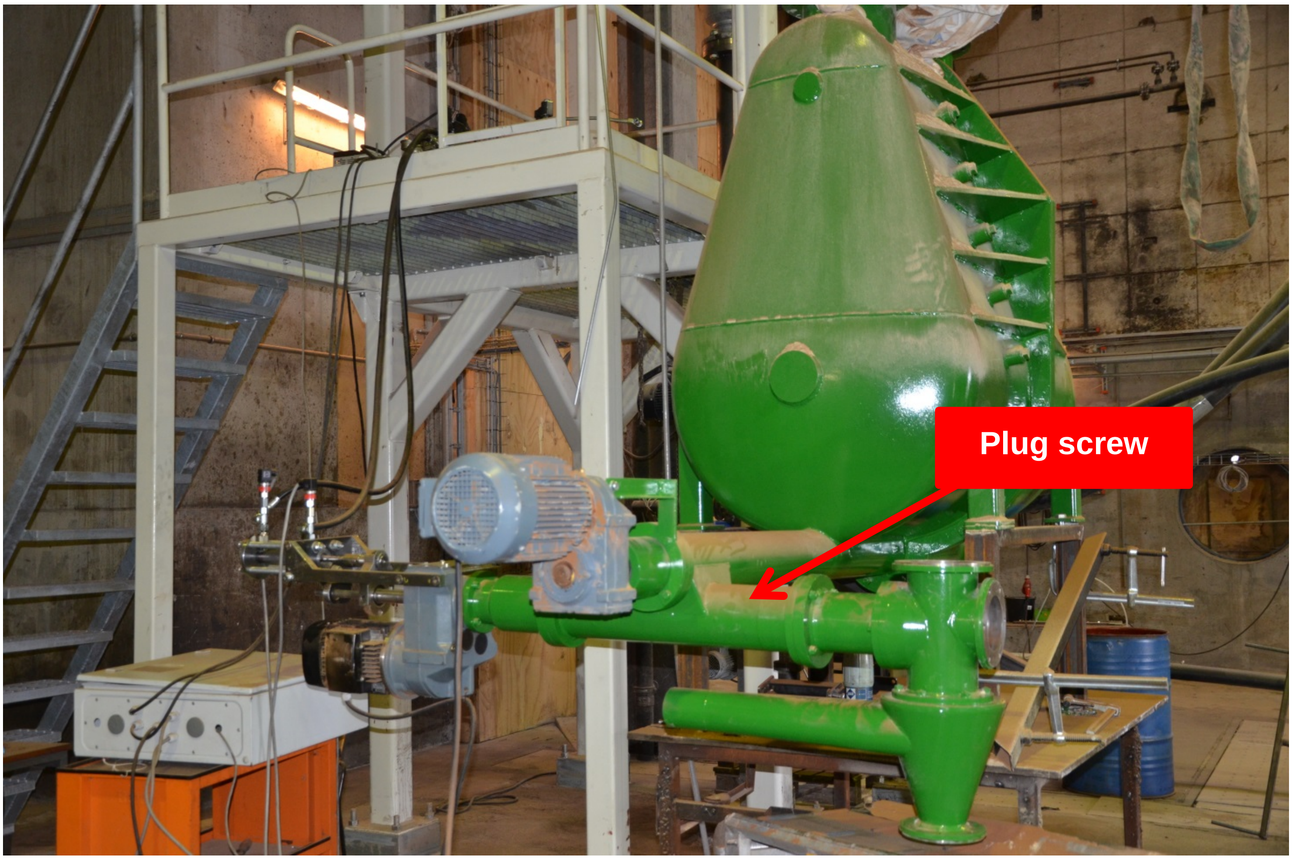


Figure 36 Picture showing the location of the plug screw

The plug screw has two controlled parameters:

- The velocity of the screw is controlled by a motor and a frequency converter
- The position of the screw is controlled by a hydraulic system. If the plug is getting too hard, the piston pushes the screw forward resulting in a shortening of the plug. If the plug is too short or too soft, the screw is pulled back, increasing the hardness of the plug.
  The suitable length of plug varies with the properties of the material fed. This control is done by measuring the pressures in the hydraulic cylinder.

On the other end of the plug screw, at the outlet, the system is equipped with a rubber piece.

The screw has a variable pitch, which is gradually smaller at the end of the screw. This design has the function of compressing the conveyed material into a plug.

The rubber piece provides a friction force to the conveyed material. This friction starts up and maintains the plug between the end of the screw and the outlet of the system.

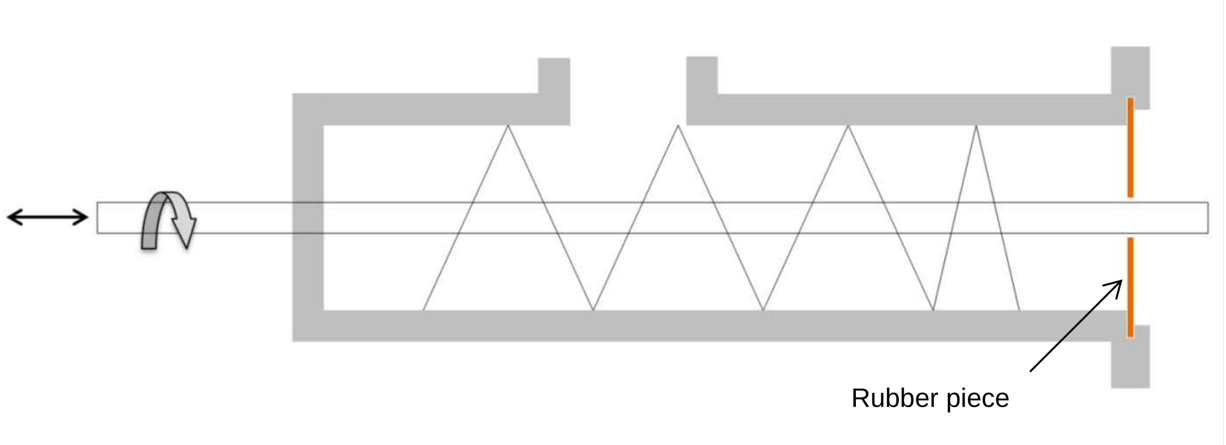
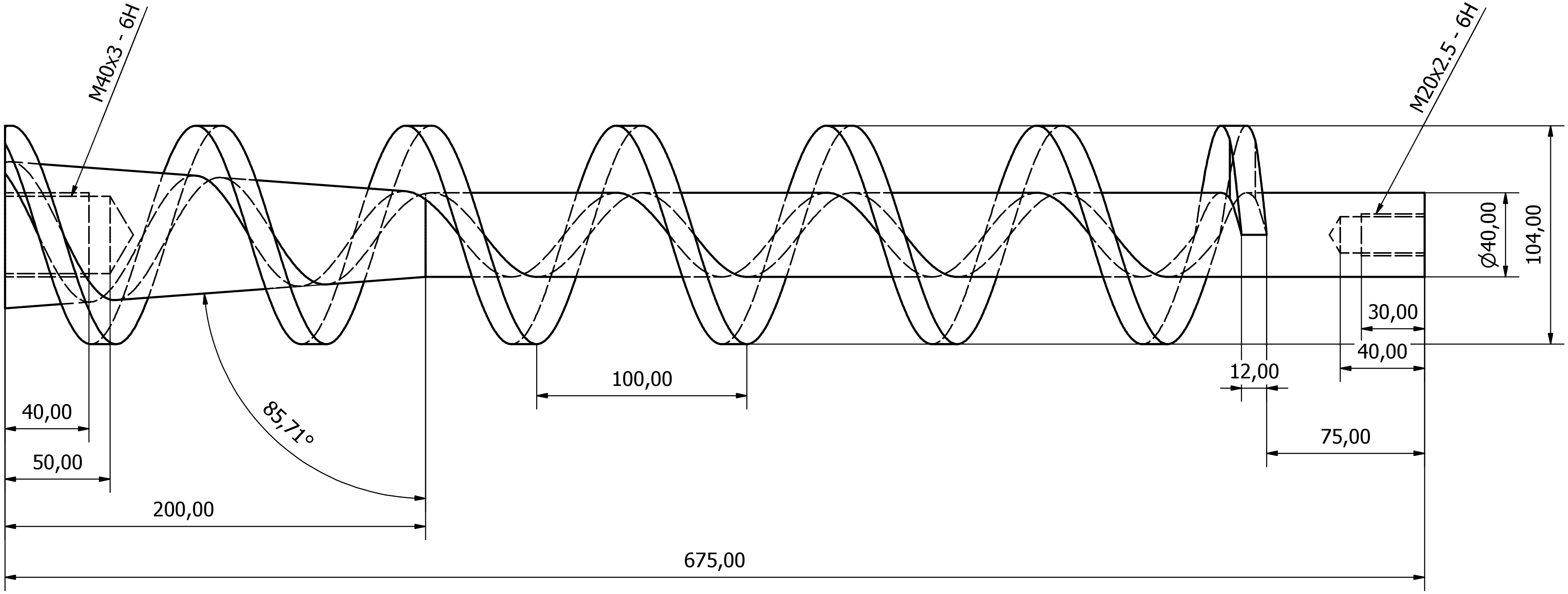
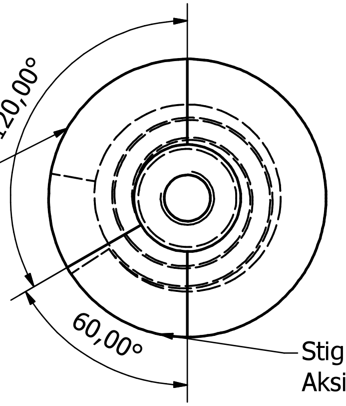


Figure 37 Sketch of the plug screw principle

A drawing of the plug screw is presented next page.





Stigning: 50 mm
Aksial afstand: 50/3=16,67 mm

Stigning: 33 mm
Aksial afstand: 33/6=5,5 mm

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4.3.4. Injection

The material must now be injected into the gasifier. The injection unit has different functions:

- Injection of the fuel material
- Inject of the oxygen or air

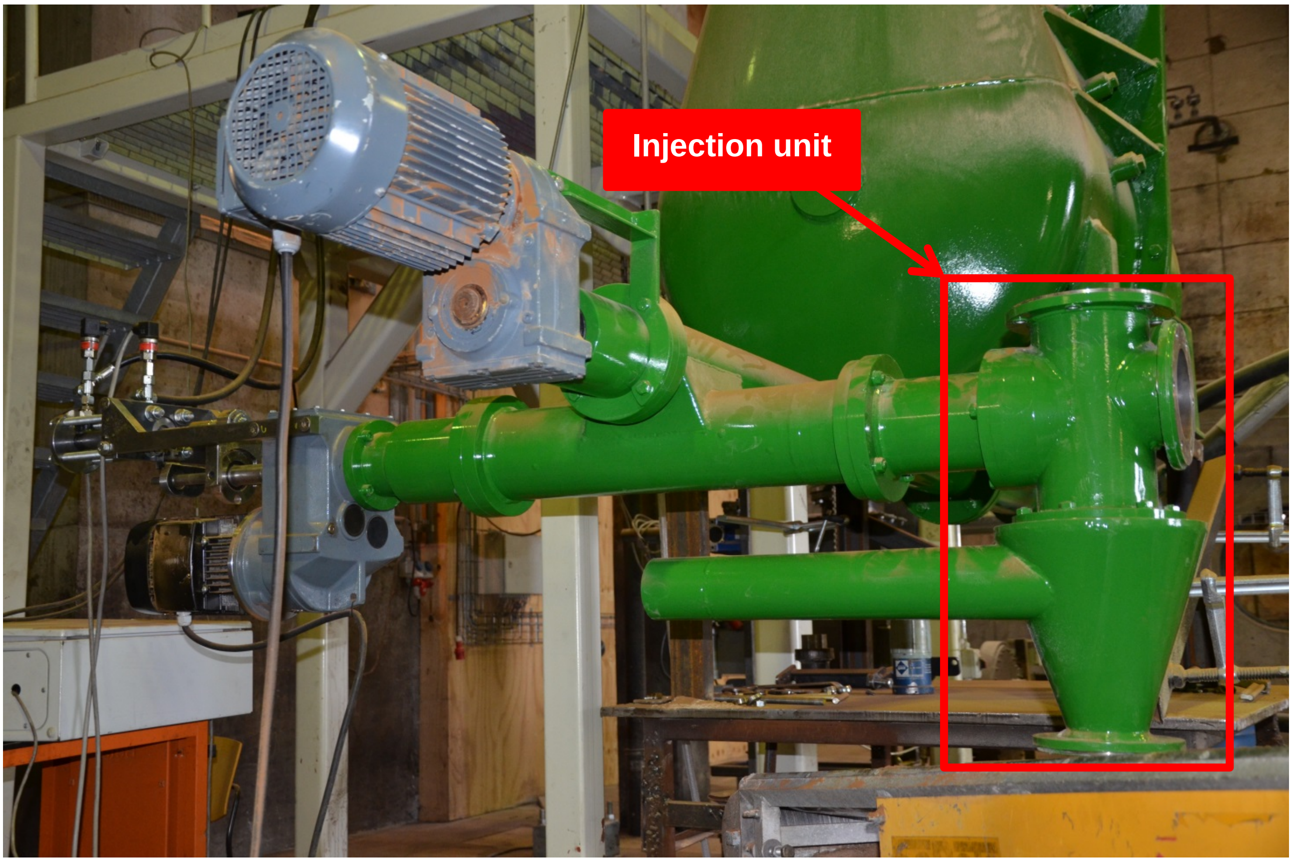


Figure 39 Picture of the injection unit housing

The injection unit consists of a vertical screw, with a conical shape, rotating at high speed (710 rpm). The screw takes the material coming from the plug screw and transports it into the injection pipe.

Around the screw housing is the inlet of oxygen or air. The design has been made in a way where the oxygen or air is mixed with the fuel, and where the gas helps injecting the fuel into the gasifier.

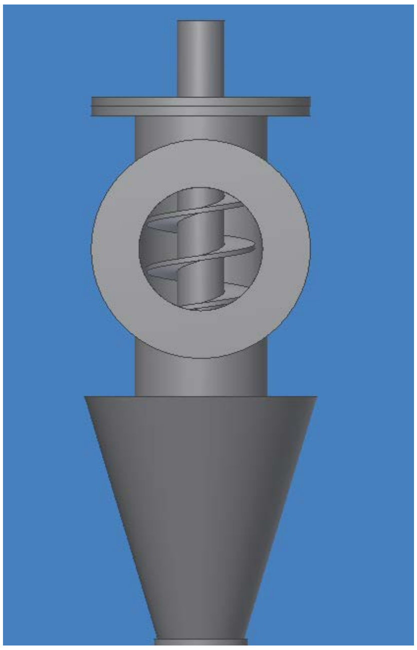


Figure 40 Sketch of the injection unit

Underneath the injection unit is mounted an injection pipe. The injection pipe has a double wall design. In the centre is flowing the mix of fuel material and air/oxygen whereas in the outer pipe is injected starting fuel.
The fuel used for starting is propane. It is used for heating up the gasifier. When the gasifier is hot, the fuel is slowly switched from propane to biomass fuel material.

Figure 41 Picture of the injection pipe

4.3.5. Gasification

The last main component of the demonstration plant is the gasifier. The supply line, from storage to injection has been designed in order to reach 10 MWth. Before testing a 10 MWth gasifier, a 3 MWth gasifier has been made in this project. The purpose of this 3 MWth gasifier is testing the technology. The data obtained on the 3 MWth can then be used for the design and upscaling of the reactor.

4.3.5.1. Reactor

The 3MWth gasifier developed is a cylindrical and horizontal entrained flow reactor with a length of 1750 mm and an inner diameter of 380 mm. The operating temperature is expected to be between 1400 and 1700 °C. The gases are burned directly at the outlet which is open.

Figure 42 Picture of the gasifier

The gasifier has a 25 mm thick concrete layer on the inside. This concrete layer protects the gasifier outer-shell during starting phase but is expected to be progressively replaced by a slag layer during operation.

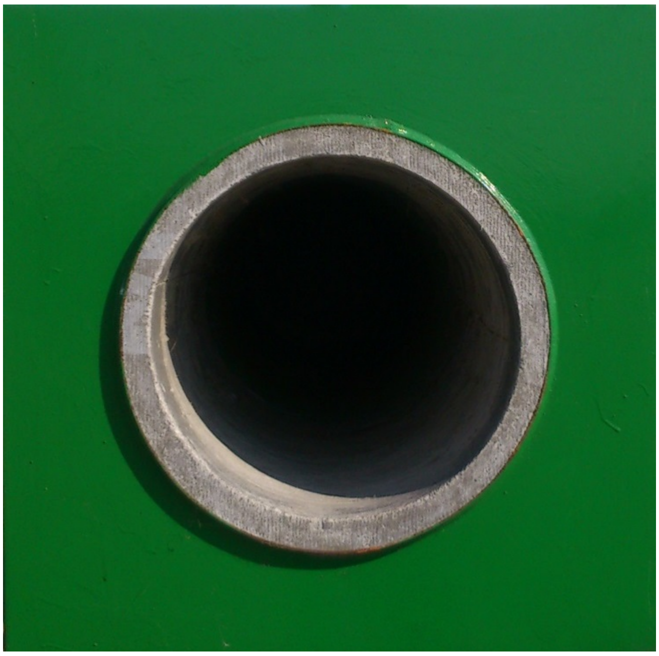


Figure 43 Picture of the gasifier (outlet) and its concrete inner layer

The gasifier is cooled by water flowing in a double wall. The gasifier has three independent cooling sections (300 mm / 1300 mm / 1300 mm). The cooling sections allow a temperature regulation of the 3 parts of the reactor by controlling the water flow.

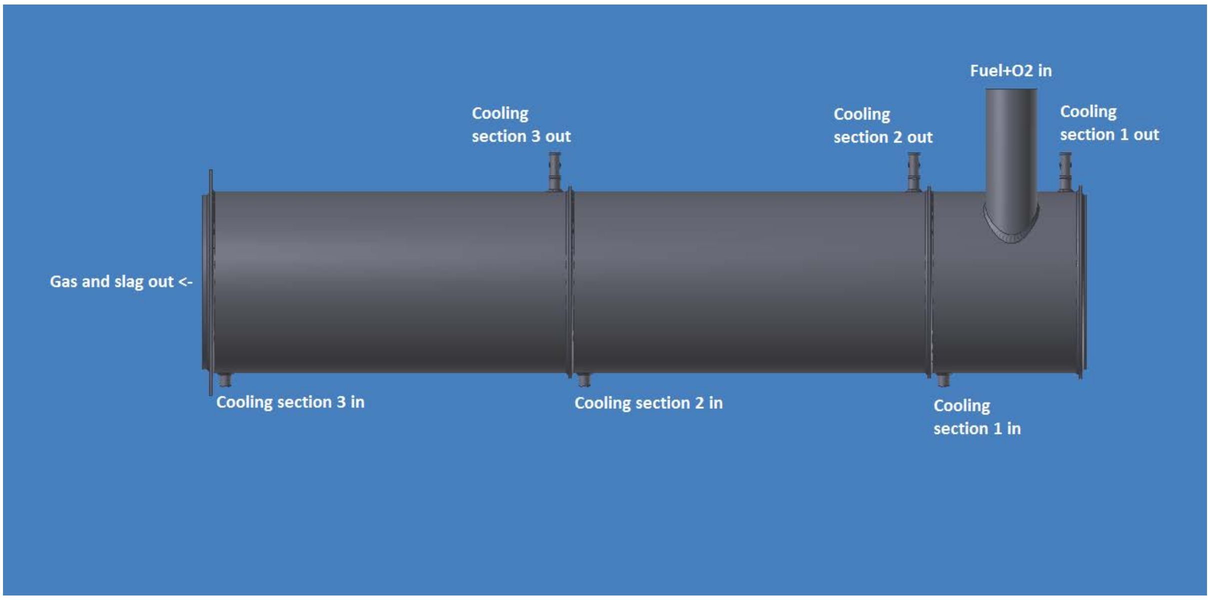


Figure 44 Sketch of the gasifier sections

4.3.5.2. Cooling system

As presented previously, the gasification reactor has 3 separated cooling sections. The cooling loop is composed of a water storage, a pump, valves and flowmeters and is presented on the following diagram.

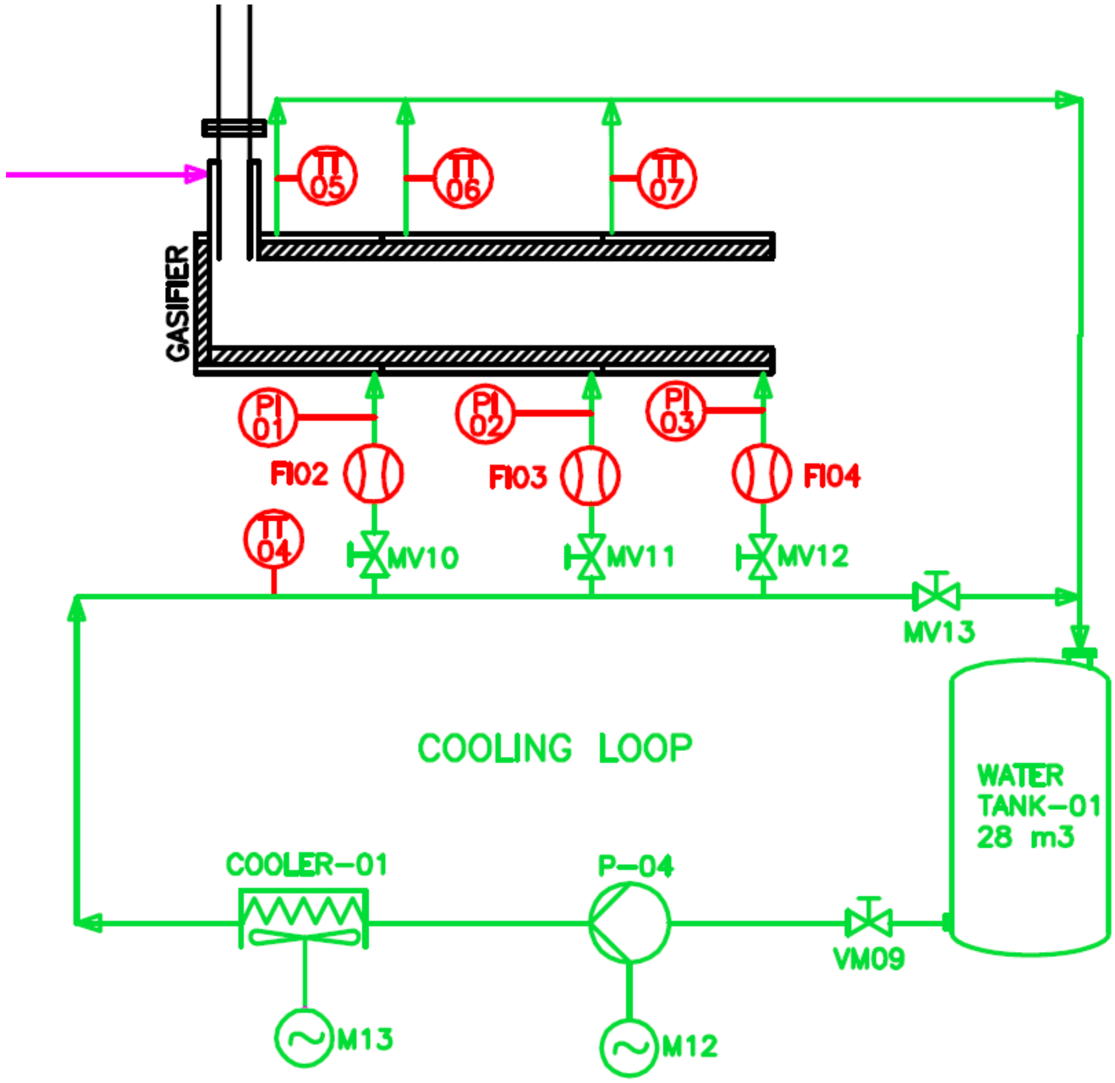


Figure 45 Diagram of the gasifier cooling system

The water storage is a cylindrical tank with a capacity of 28 m^3. This big volume is used as a buffer and limits the increase of the water temperature. At the bottom of the tank, the water is pumped by a centrifugal pump (Trium LMT63Å) with a capacity of 30 m^3/h. The water then goes through a heat exchanger (Flexcoil VTED-141-V-9) with a cooling capacity of 200 kW.

The water flow in each section is adjusted by the manual valves MV-10, MV-11 and MV-11 and measured by the flow meters FI-02, FI-03 and FI-04 (KAMSTRUP Ultraflow 54). There is a measurement of the water temperature at the inlet and at the outlet of each section. There is also a pressure measurement in each cooling section.

After cooling the reactor, the water goes back to the water storage.

With the flow vs the temperature increase in each cooling section, the cooling power is then known.
TK Energy has some experience in slag walls in entrained flow reactor and a good estimation of the internal temperature profile of the reactor could be deduced from the cooling power values.

The expectations concerning the cooling system are:

Reactor heat loss to cooling	300	kW/m2		
Water temperature cold	40	°C		
Water temperature hot	60	°C		
Water flow	6,5	kg/s	23,4	m3/h
Cooling needed	544	kW		

The system is expected to be started with preset cooling flows and then adjusted in function of the temperature values at the outlet of each section.

4.3.5.3. Propane supply

As already mentioned, the gasifier is started with propane as fuel. This heating up phase is estimated around 1 hour.
Hereunder is presented the propane supply line:

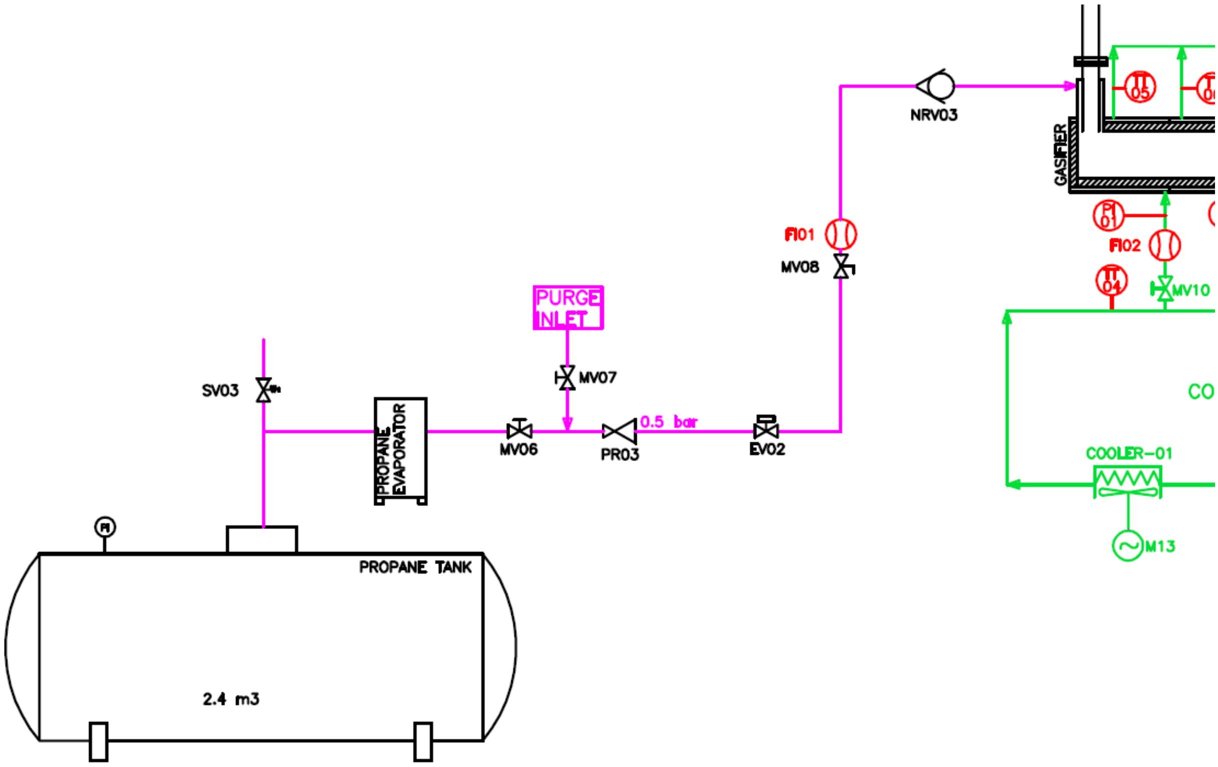


Figure 46 Diagram of the propane supply line

The main components of the propane supply line are storage tank for liquid propane (2.4 m^3), an evaporator, a pressure reduction valve, a shutdown valve, an adjustment valve and a flowmeter.

The flow of propane is adjusted by the manual valve MV-08. The propane flow is measured by the flowmeter FI-01. The flowmeter FI-01 consists of an orifice plate and a differential pressure transmitter.

The figure below shows the curve of the propane mass flow in function of the differential pressure, according to the gas line and orifice plate specifications:

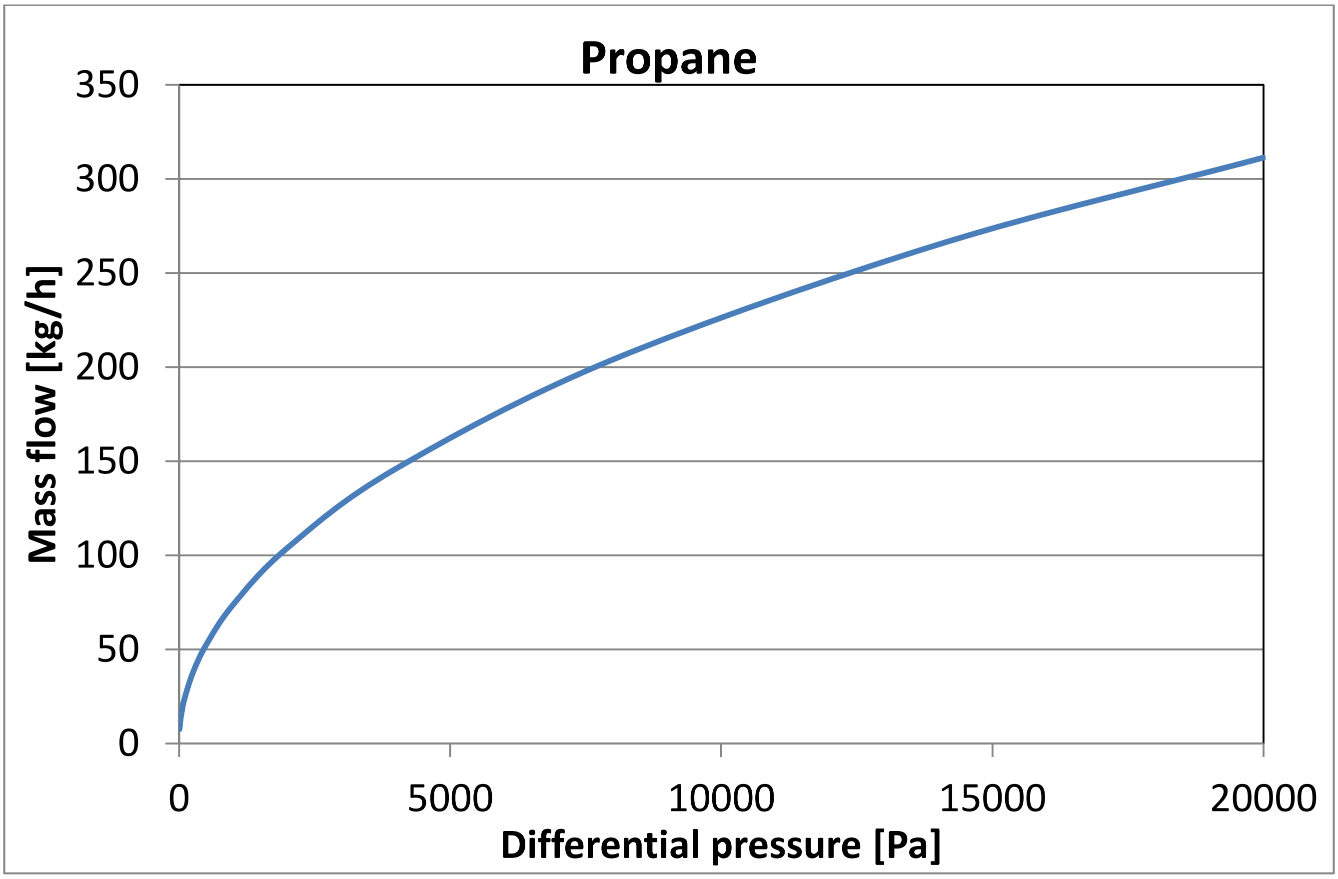


Figure 47 Graph of propane mass flow vs. differential pressure across orifice plate

4.3.5.4. Oxygen/air supply

In the burner is injected a mix of oxygen and air. During the heating up phase, pure oxygen is injected into the reactor for an optimal combustion of the propane. After propane has been slowly replaced by biomass fuel, the percentage of oxygen can be lowered by injection of air.

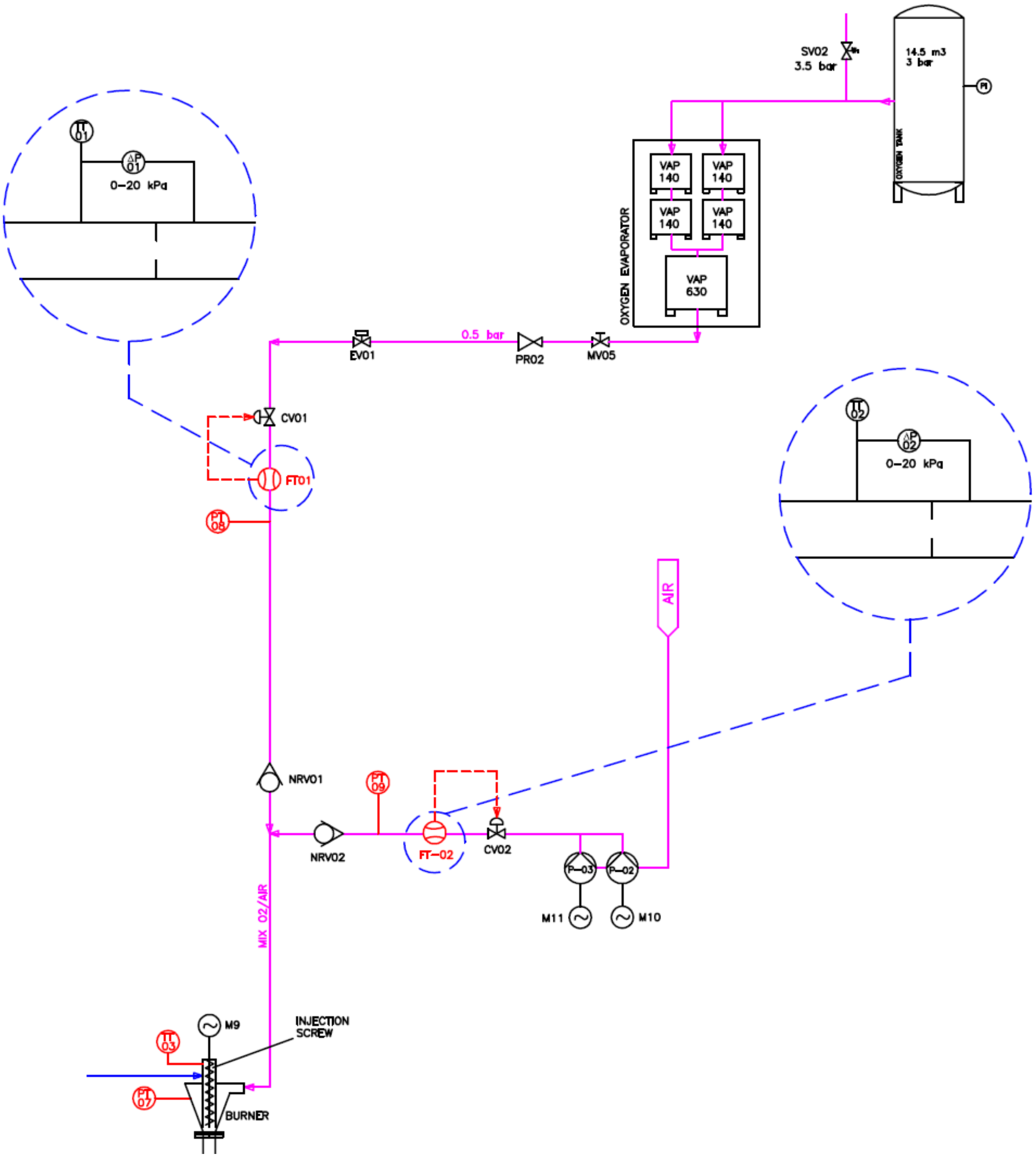


Figure 48 Diagram of the oxygen and air supply system

The oxygen supply line consists of a 4.5 m^3 tank of liquid oxygen, an evaporator, a pressure reduction valve, a shutdown valve, a control valve, and a flowmeter.

The flowmeter FT-01 consists of an orifice plate, a differential pressure transmitter and a temperature measurement.

The pipe size will be the same for both 3 and 10 MWth gasifiers:

- Oxygen: Ø 100 mm
- Air: Ø 250 mm

However, the orifice plates for flow measurement have the following dimensions:

- 3 MW
  - Oxygen orifice: Ø 31 mm
  - Air orifice: Ø 80 mm
- 10 MW
  - Oxygen orifice: Ø 53 mm
  - Air orifice: Ø 137 mm

From these orifices the following figures are calculated with flow as a function of pressure.

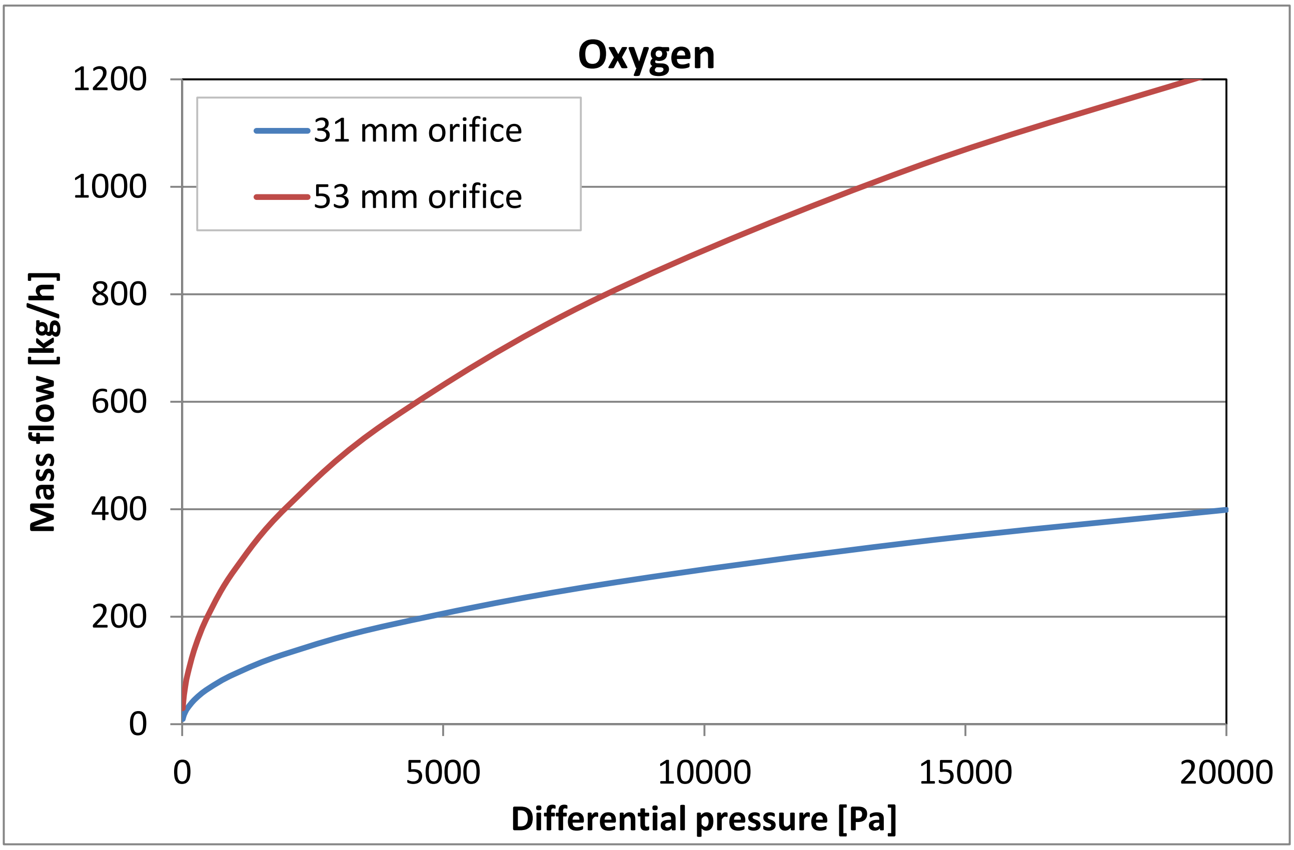


Figure 49 Graph of oxygen mass flow vs. differential pressure across orifice plate

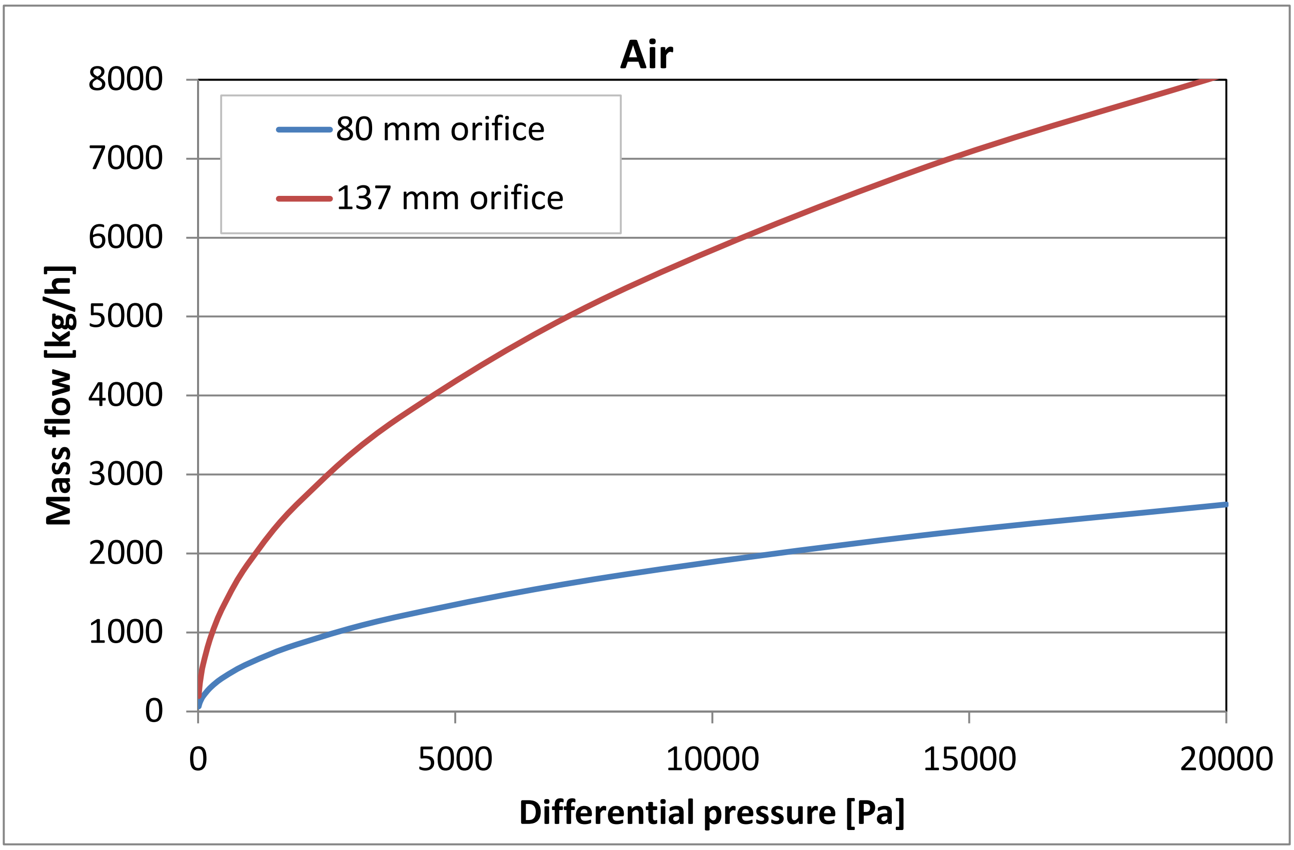


Figure 50 Graph of air mass flow vs. differential pressure across orifice plate

4.4. Tests and results

4.4.1. Drying

The load of the dryer is monitored from the 4 load cells mounted underneath. After loading, the drying process can be monitored and the weight evolution recorded. The graph below shows the drying evolution of 14 tons of sewage sludge drying over a week.

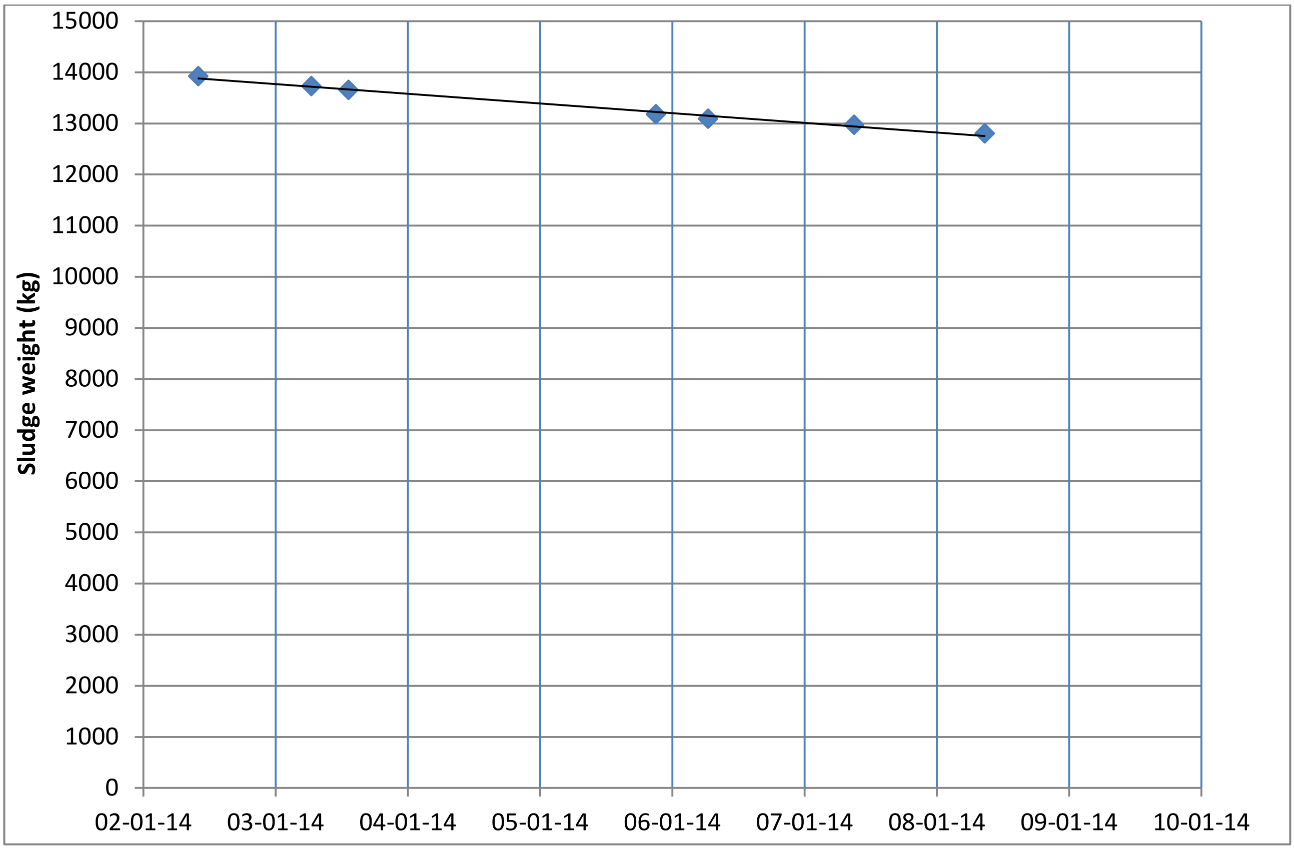


Figure 51 Graph of sewage sludge weight vs. Time during drying in the container

The dryer is loaded with approximately 14 tons of sewage sludge with moisture content of about 50%. The moisture content is however difficult to determine accurately as it is not homogeneous. The moisture measurement method is presented in annex 1.

As the dryer is open on the top, a correction of the measurement considering the rainfall is made. The rainfall over the time period of the measurement was 8 mm for an opening area of 8.5 m^2. The resulting weight to be added to the water evaporated is then 68 kg.
The average evaporation rate measured is 8.5 kg/h.

The moisture content of the sludge can be here estimated to be around 45% after a week of drying. However, the moisture content is actually much lower in the bottom of the container, where the material is first fed into the process. Further tests have shown that the sewage sludge in the bottom was dry enough to be handled by the demonstration facility.

4.4.2. Stone removal

The stone removal system has endured operational tests only. First, a prototype (scale 1:2) has been built and tested. Few modifications have been made on the rotating smashing pieces (shape, number, size). Finally, an up-scaled version has been built and tested. The smashing pieces are steel chains. The system can smash sewage sludge clumps and handle big stones (Ø50-100 mm), wood pieces (500 mm long) or steel pieces. These unwanted materials can then be removed from the lateral trapdoor.

The stone removal system has been tested in-line with the rest of the process up to 4.2 tons/h of sewage sludge (moisture content < 25%), corresponding to a volumetric flow of 6 m^3/h and a power of 12 MW. The stone removal system has been working perfectly in these conditions.

4.4.3. Feeding

The feeding bin has been first tested separately with wood chips and has shown a very constant operation. The design of the feeding bin ensures a full filling of the screw. Further tests with sewage sludge have been also conducted and have shown the same results.

During the tests, few functions have been added. A light (inside) and a lateral window have been added in order to be able to observe the level of material present in the feeding bin.

Through this window, the behaviour of the material inside the feeding has been observed and a judicious position for the level detection sensor has been chosen. The sensor is connected to the PLC which controls the movement of the container screws motors. If a high level of fuel is detected in the dosing bin, the PLC stops the container screws.

An extra observation window has also been made on the outlet pipe of the feeding bin. At high flow of material, problems in the feeding line have made it necessary to observe the density of the fuel material fed into the hammer mill.

The feeding screw was operated up to 4.2 tons/h of sewage sludge (moisture content < 25%), corresponding to a volumetric flow of 6 m^3/h and a power of 12 MW.

4.4.4. Downsizing and pneumatic transport

First, the hammer mill was tested with wood chips. The wood chips were easily downsized, with a power consumption below 20 kW. The resulting saw dust was composed of millimetric particles.

Then assembled with the rest of the demonstration facility, the hammer mill was tested with sewage sludge (moisture content < 25%). The hammer mill can downsize the sewage sludge into a micrometric and uniform powder with a power consumption around 10 kW.

The hammer mill can handle the downsizing of 4 tons/h of sewage sludge. At higher flow, the pneumatic transport loop is clogging up between the hammer mill and the cyclone. The suspected reason for this problem is a decrease of the inlet air flow into the hammer mill.

Above 4 tons/h, the sewage sludge starts to close the air inlet when going into the hammer mill. Without enough air, the hammer mill loses its fan effect which is supposed to carry the downsized powder up to the cyclone. Material starts accumulating in the pneumatic transport loop and ends clogging it up totally.

In order to check this hypothesis, a flowmeter is set up on the back loop of the pneumatic transport system, just before the hammer mill inlet. It consists of an orifice plate and a differential pressure transmitter. The idea is monitoring the air flow while increasing progressively the sewage sludge flow.

4.4.5. Separation of the solid particles from the air flow

The cyclone design and principle was validated by a test with saw dust showing a good separation efficiency. The solid particles fall well through the bottom of the cyclone while the air exiting the top of the cyclone contains only very small particles (dust) and in a limited amount.

The cyclone has then been mounted on top of the dosing bin in order to be tested within the demonstration facility. Tests with sewage sludge powder have not shown any problem concerning the cyclone.

4.4.6. Dosing and injection

Dosing and injection experiments have been the main focus of this project. Many different experiments have been made in order to know and improve the dosing and injection system.

Before being set-up together with the rest of the demonstration facility, the dosing bin, the plug screw, and the injection screw have been tested separately through many experiments.

The sketch on the next page shows the experimental setup for testing.
The filling of the dosing bin is conducted by a long feeding screw. The second top flange of the dosing bin is equipped with a funnel and is used as an extra inlet.
At the outlet, a belt conveyor transports the powder into a weighing bin positioned on top of a bench scale. The dosing is characterized by measuring the mass of powder falling into the weighing bin over different spans of time.
The observation of the powder distribution on the conveyor belt gives also interesting information about the flow uniformity.

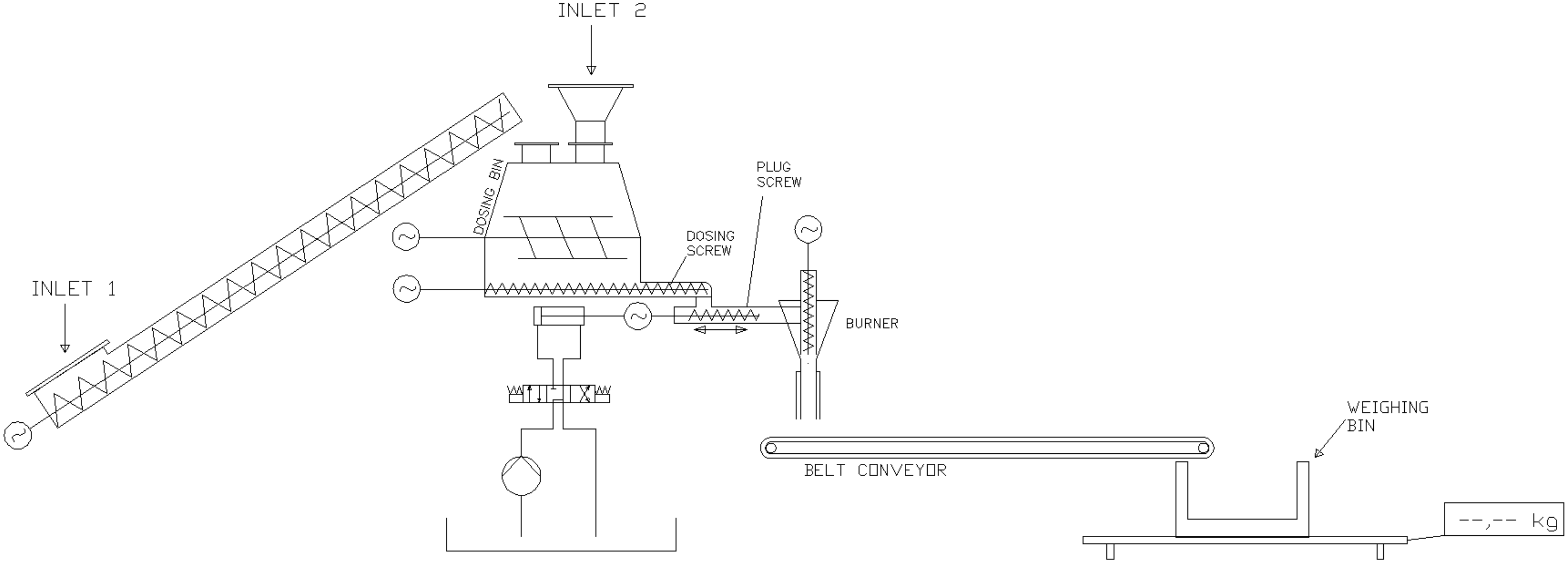


Figure 52 Sketch of the experimental test facility for dosing and injection

Hereunder are described the different operational and experimental tests conducted on these 3 components.

4.4.6.1. Dosing bin

Level measurement

In its upper part, the dosing bin had initially a rotating shaft on which were welded flights (see red arrow on figure 35). The system is driven by an asynchronous motor. When the dosing bin gets filled, the system moves material and uses more power.
By monitoring the power consumption of the motor, it can then be detected when the dosing bin is full or not.

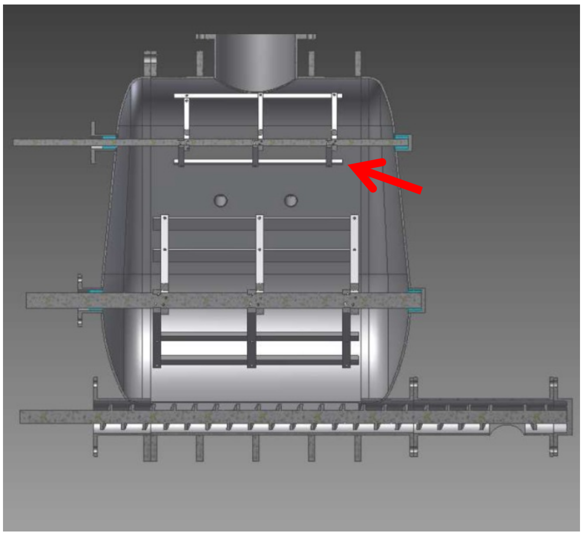


Figure 53 Preliminary dosing bin version with level detection system

This level detection system works with high density materials. However, with light powders, the power consumption is so little that the detection is not reliable. One of the focus of this development project being the versatility of the technology, it has been decided not to use this system for the level detection.

Further tests, where the torque of the bridge breaker was monitored have shown better results. The bridge breaker being bigger than the level detection system, it moves more material; it was observed that the torque gives a good idea of the level in the dosing bin. Low and high density materials can be detected as shown on the following graph.

The torque measurement method is presented in annex 2.

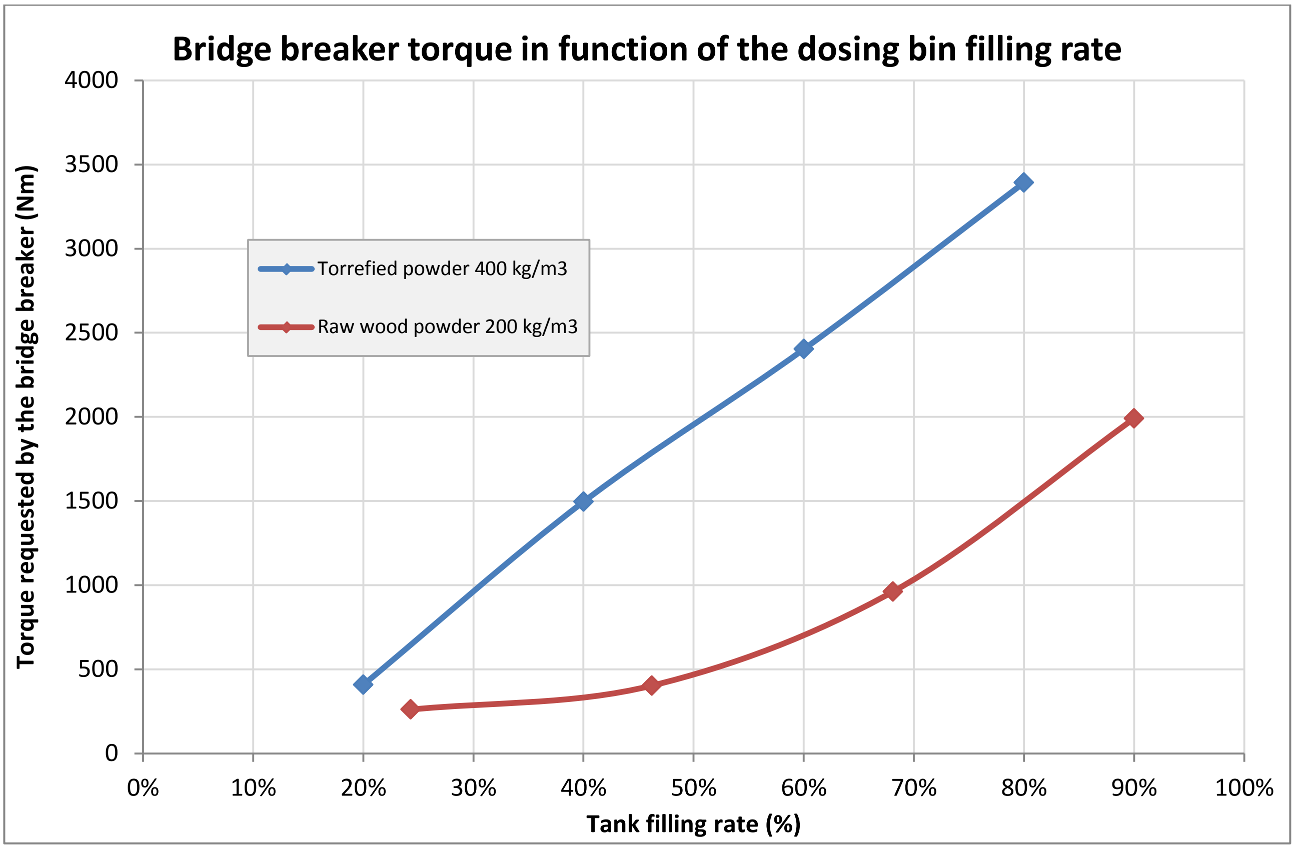


Figure 54 Bridge breaker torque vs dosing bin filling rate

The graph shows the torque needed for rotating the bridge breaker in function of the filling rate of the dosing bin.
The blue curve corresponds to measurements with torrefied wood powder which has a density around 400 kg/m^3 whereas the red curve corresponds to measurements with raw wood powder which has a density around 200 kg/m^3.

This principle implies a pre-test each time a new material is treated by the facility in order to characterize the torque (or power) in function of the level of the material concerned.

Dosing accuracy

The accuracy of the dosing has then been tested. The experiment has consisted in measuring the mass flowrate of wood powder dosed by the system in function of the amount of powder present in the dosing bin.

The first graph shows the mass flow distribution at 2 different screw velocities.

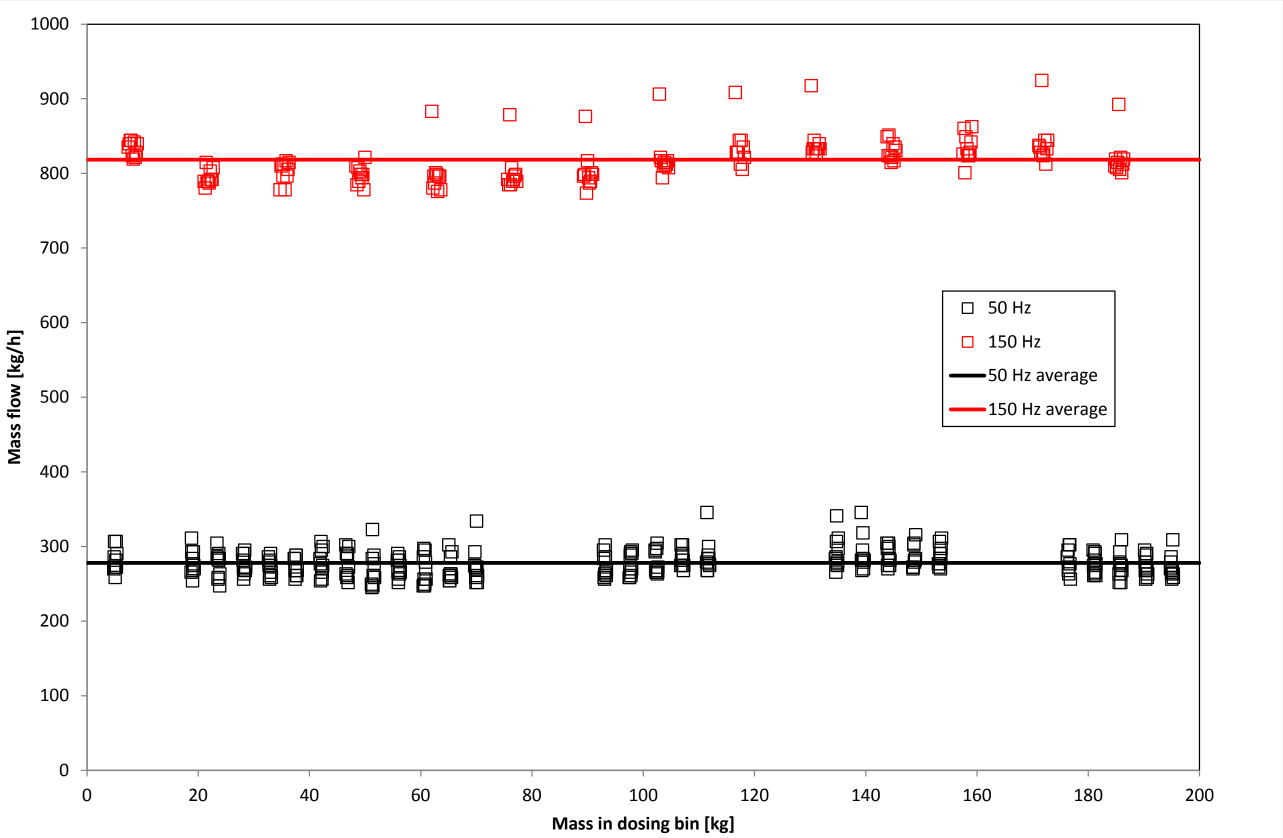


Figure 55 Graph of the mass flow evolution vs. the mass of material present in the dosing bin with long dosing screw

The average mass flow is pretty constant whereas the quantity of wood powder is changing inside the dosing bin. However some fluctuations up to 15% of the average mass flow are observed for the same quantity of wood powder in the dosing bin. In order to reduce these fluctuations, the dosing screw has been shortened resulting in a formation of a small dune of material at the outlet of the dosing screw. This modification has improved the dosing accuracy as shown by the following graph where the same experiments have been conducted again.

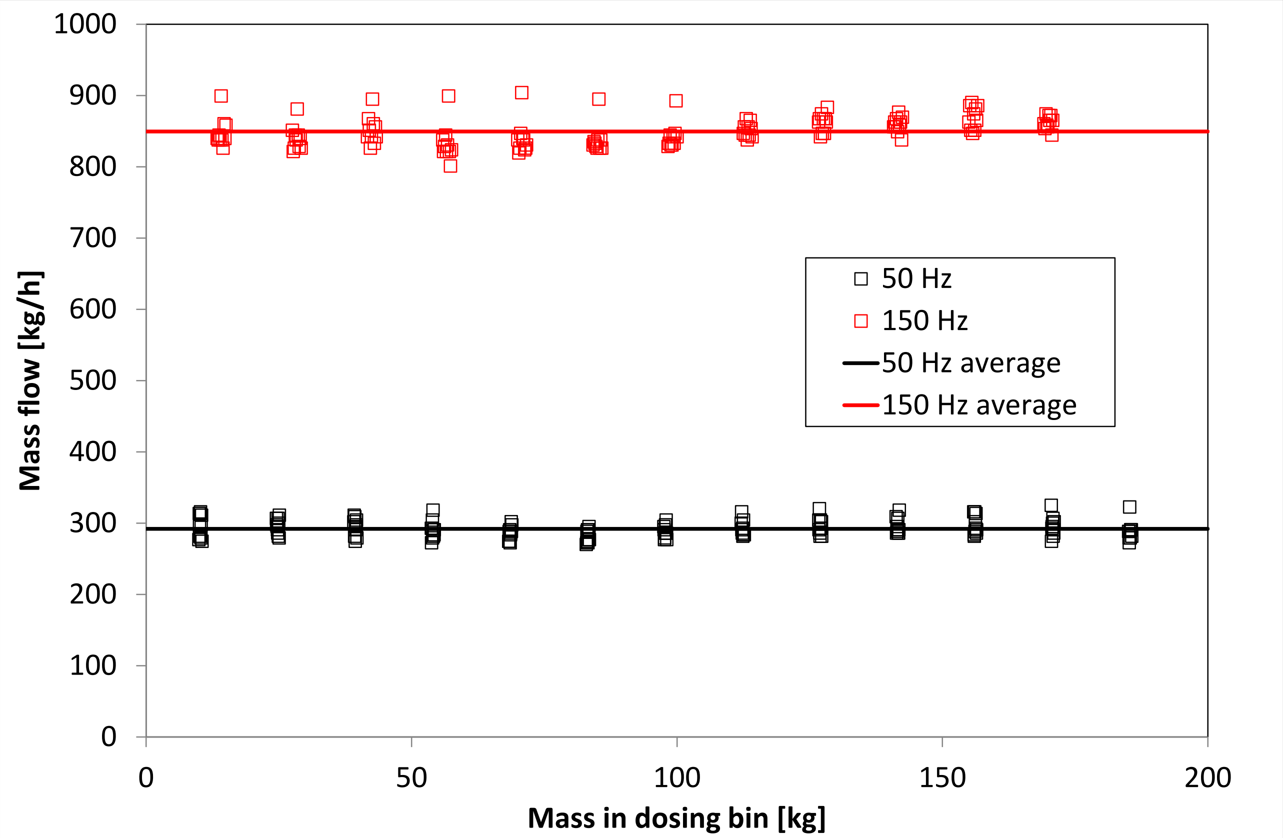


Figure 56 Graph of the mass flow evolution vs. the mass of material present in the dosing bin with short dosing screw

The fluctuations are reduced to about 6% of the average flowrate. These new results are satisfactory.

Dosing capacity

The dosing bin is the component setting the flow of fuel material for the process. Therefore it is essential to know the flow evolution in function of the velocity of the dosing screw.

The velocity is controlled by a frequency controller supplying power to the motor of the dosing screw.

Measurements of the mass flow have been made on the frequency range from 10 to 100 Hz (corresponding to a screw velocity of 18 to 180 rpm). The mass flow has then been converted into a volumetric flow and its evolution is shown on the following graph.

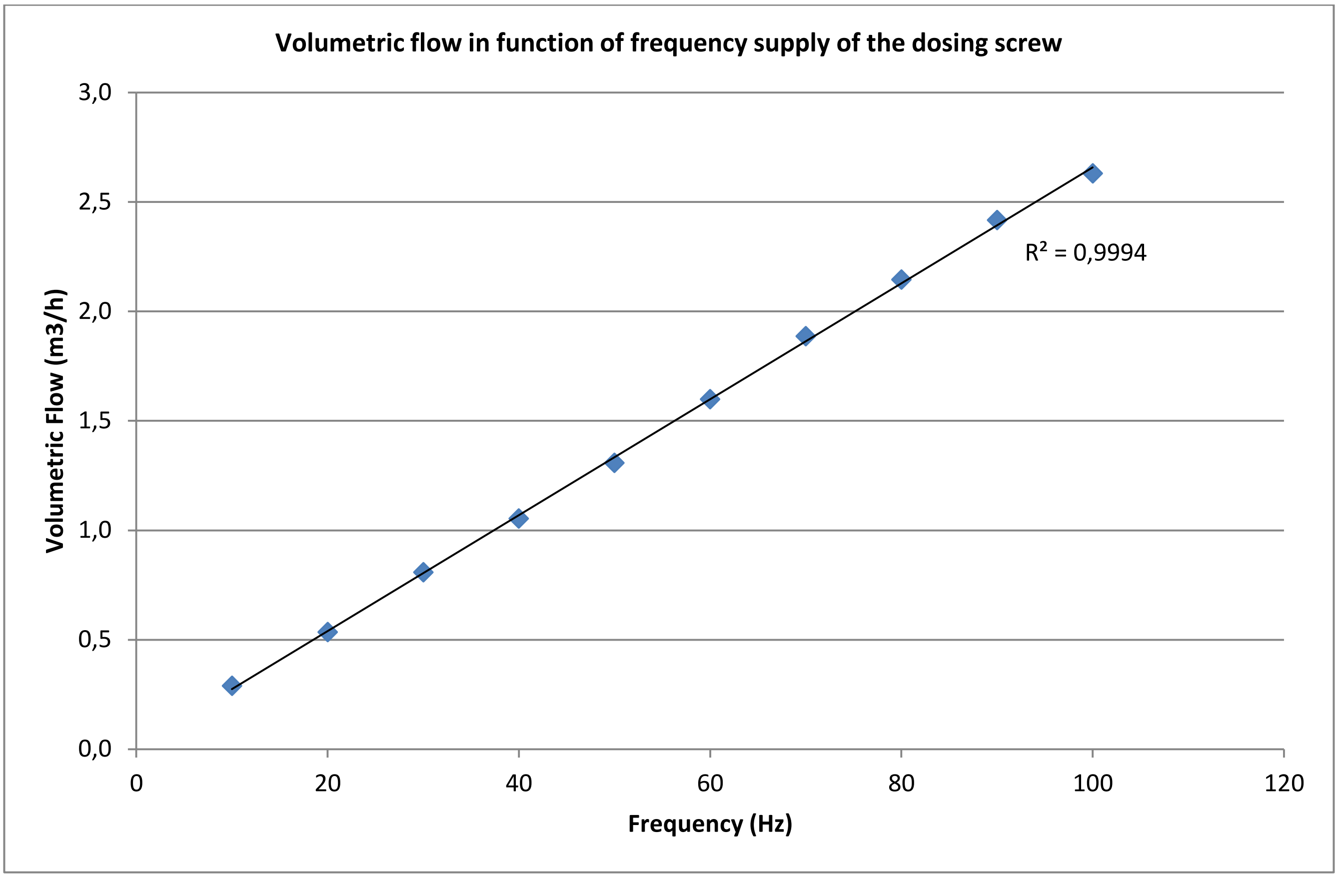


Figure 57 Volumetric flow out of the dosing bin vs. frequency

The graph shows good linearity of the volumetric flow when the velocity of the dosing screw is increase. It can be deduced that the filling rate of the screw is very constant and the bridge breaker very efficient.

The dosing bin can provide 2.6 m^3/h of material at a frequency of 100 Hz. In order to reach 3 MW with wood powder, the system will have to provide 3 m^3/h by slightly increase the dosing screw velocity by supplying the motor at 115 Hz.

4.4.6.2. Plug screw

Once assembled and mounted at the outlet of the dosing screw, the plug screw has endured many experiments. Improvements were made on the shaft, the rubber plugging piece and the actuating control system.

Shaft

Primary tests have shown that the soft plug of powder was falling apart at the end of the shaft. The shaft has been extended in order to help holding the plug until the end of the pipe.

The two following pictures illustrates this small change that has however an important effect.

Figure 58 Pictures with short and extended shafts

On the left picture it can be seen the soft plug falling apart. The sealing function is then affected and it cannot be expected that this soft plug can handle any pressure variations.
On the right picture however, the extended shaft is sticking out of the pipe and contribute in holding the plug until the end of the pipe. The plug is more solid and can be expected to handle some pressure variation.

Rubber plugging piece

As it can be seen on the right picture of the figure 58, a rubber piece is also present at the outlet of the plug screw pipe.

The function of this rubber piece is creating and maintaining the soft plug. By applying counter force to the flow of powder, the rubber piece starts the plug building. It then helps maintaining it when powder is going through the plug screw as well as when the screw is stopped.
This rubber piece has to suits materials with different mechanical properties in order for the process to be able to handle different fuels without changing this piece.

Different rubber piece designs have been tested. Hereunder are described the different tests and the final solution chosen.

Three variable parameters have been changed over the tests:

- The type/thickness of rubber (4-6 mm)
- The size of the central hole (40-90 mm)
- The number of cuts (0-12)

The following picture shows some of the rubber pieces tested.

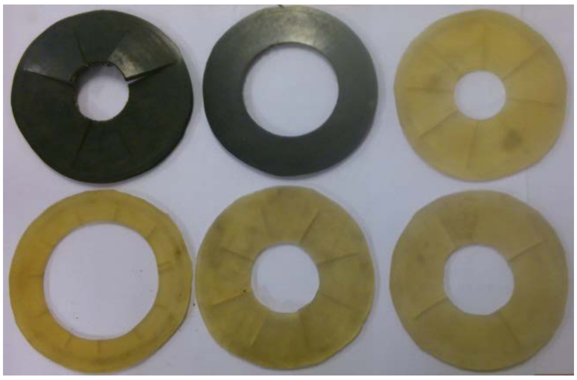


Figure 59 Picture of some of the rubber plugging pieces tested

For each rubber piece, the position of the screw and the power consumption of the motor driving the plug screw have been recorded. Have been eliminated, the one:

- Resulting in high power consumption of the screw motor
- Operating in a very defined range of position
- Requiring a long movement of the screw when switching the fuel material for another one

The following table summarizes the tests conducted:

rubber type	thickness (mm)	hole Ø (mm)	number of cuts	comments with CEA powder	comments with torrefied powder	result
rigid	6	90	0	screw stuck	- not tested -	× rejected
rigid	6	40	4	- not tested -	high power consumption, very hard plug	× rejected
rigid	6	40	8	- not tested -	high power consumption, very hard plug	× rejected
flexible	4	90	12	ok	no plug can start, it desintegrates	× rejected
flexible	4	90	0	ok	not working -> screw stuck due to high friction	× rejected
flexible	4	55	4	high power consumption, very hard plug	- not tested -	× rejected
flexible	4	55	8	ok	no plug, hole too big or too many cuts	× rejected
flexible	4	40	8	ok	long plug due to low friction -> too many cuts	× rejected
flexible	4	40	6	ok	ok	✓ approved

Figure 60 Recap table of the tests conducted on rubber pieces

The final choice (Figure 61) is a flexible rubber, 4 mm thick, with a Ø40 mm hole and 6 cuts. This piece permits to the plugging system to work with reasonable power consumption and with different materials.

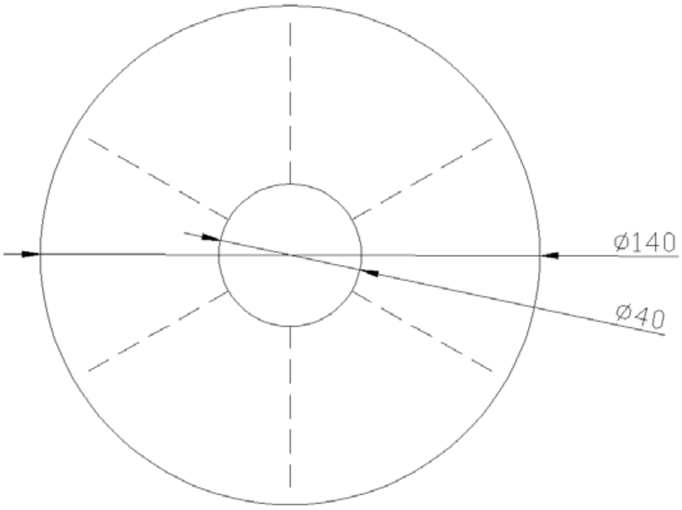


Figure 61 Design selected for the rubber piece

The design presented above has been slightly improved in order to increase the lifetime of the piece. Holes are made at the end of each cut for dissipation of the stress and for avoiding tears.

Plug screw position

The plugging system is built with the possibility of changing the axial position of the screw. This parameter gives the possibility of increasing or decreasing the plug length. Depending on the material being fed, the plug length must be adjusted in order to have the same plugging efficiency.

Two very different powders have been used for the plugging experiments. The first is a torrefied wood powder which is a non-sticky, hardly compressible and has a density of 400 kg/m^3. The second is fresh wood powder highly compressible, difficult to handle (easily bridging for example) and with a low density of about 200 kg/m^3.

With these two powders, operating position ranges have been defined. They correspond to a range of position in which the plug has good properties and where the risk of losing the plug or having the screw stuck is low. These operating position ranges are shown on the sketches hereunder.

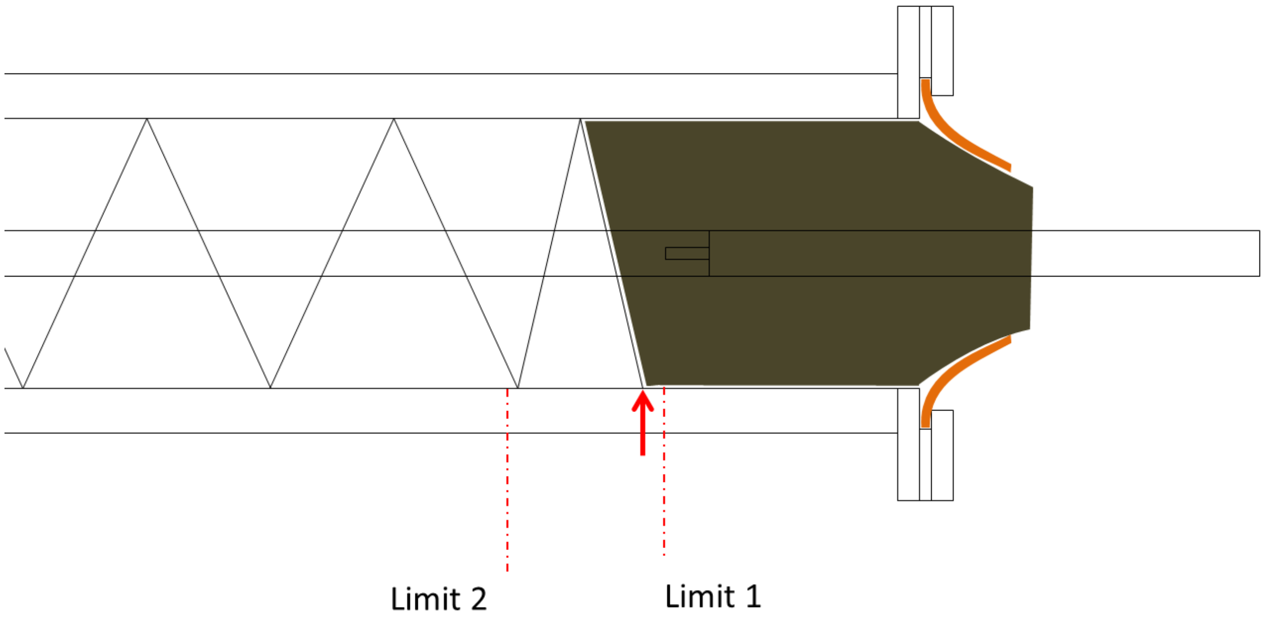


Figure 62 Suitable plug length with torrefied wood powder

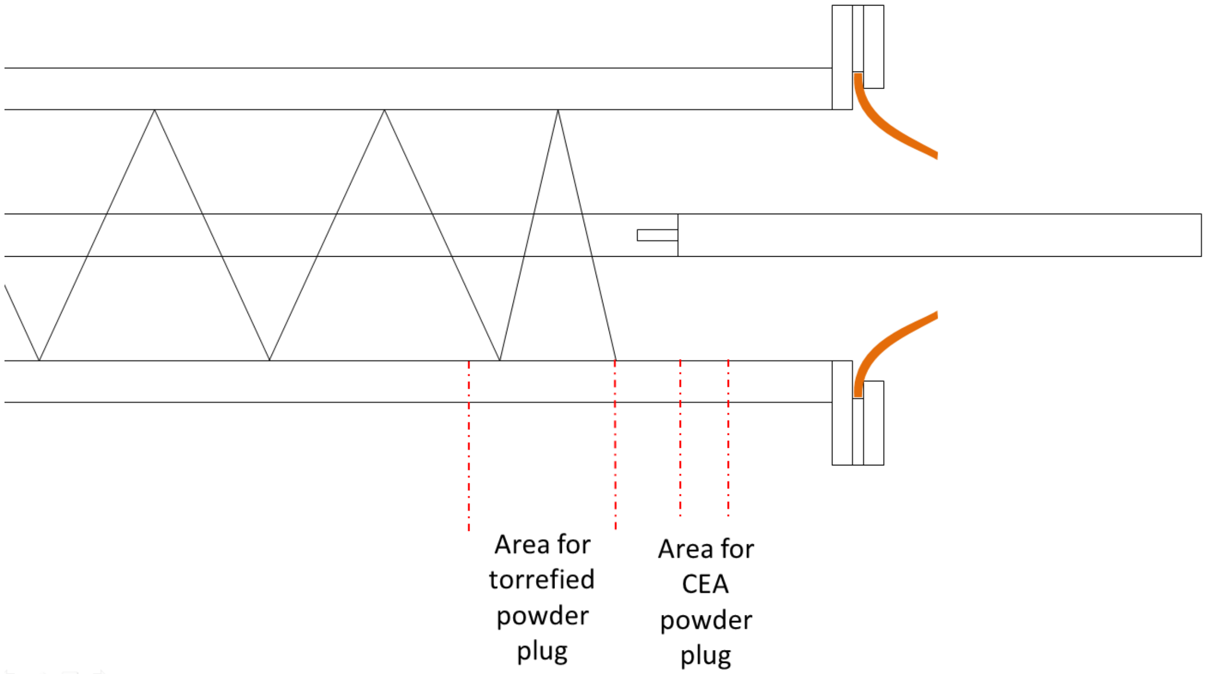


Figure 63 Suitable plug lengths for torrefied wood powder and fresh wood powder

These figures show the necessity of changing the position of the plug screw when the fuel material is changed. One option for operating could be to test the plug screw with each new kind of material that has to be handled by the process and then set the plug screw position manually each time the fuel material is changed. But the risk of damaging or stopping the process is high with this option.

Therefore it has been decided to develop an automatic position control system for the plug screw. It is presented in the following paragraph.

Control of the plug screw position

The positioning of the plug screw was initially carried out manually by an adjustment screw mounted at the back of the plug screw. With this system, it has been seen that by changing the position of the screw and so the length of the soft plug, changes in the power consumption of the motor driving the plug screw were detected pretty quickly.

However, there is one main problem with using the power consumption of the motor as a control value for the plug hardness: the sensibility to temperature.
When starting, the system is at ambient temperature. But after some operating time there is two temperature increases:

- The gearbox temperature increases, resulting in a temperature increase of the oil. At higher temperature, the oil viscosity is lower so the power consumption decreases
- The friction where the plug is formed creates heat resulting in a temperature increase at the end of the pipe. This could also affect the power consumption of the system.

Therefore it is difficult to regulate on the power consumption of the plug screw for a period that can reach several minutes, as it can be seen on the graph below. This solution is not good enough because the risk of stopping the process remains high.

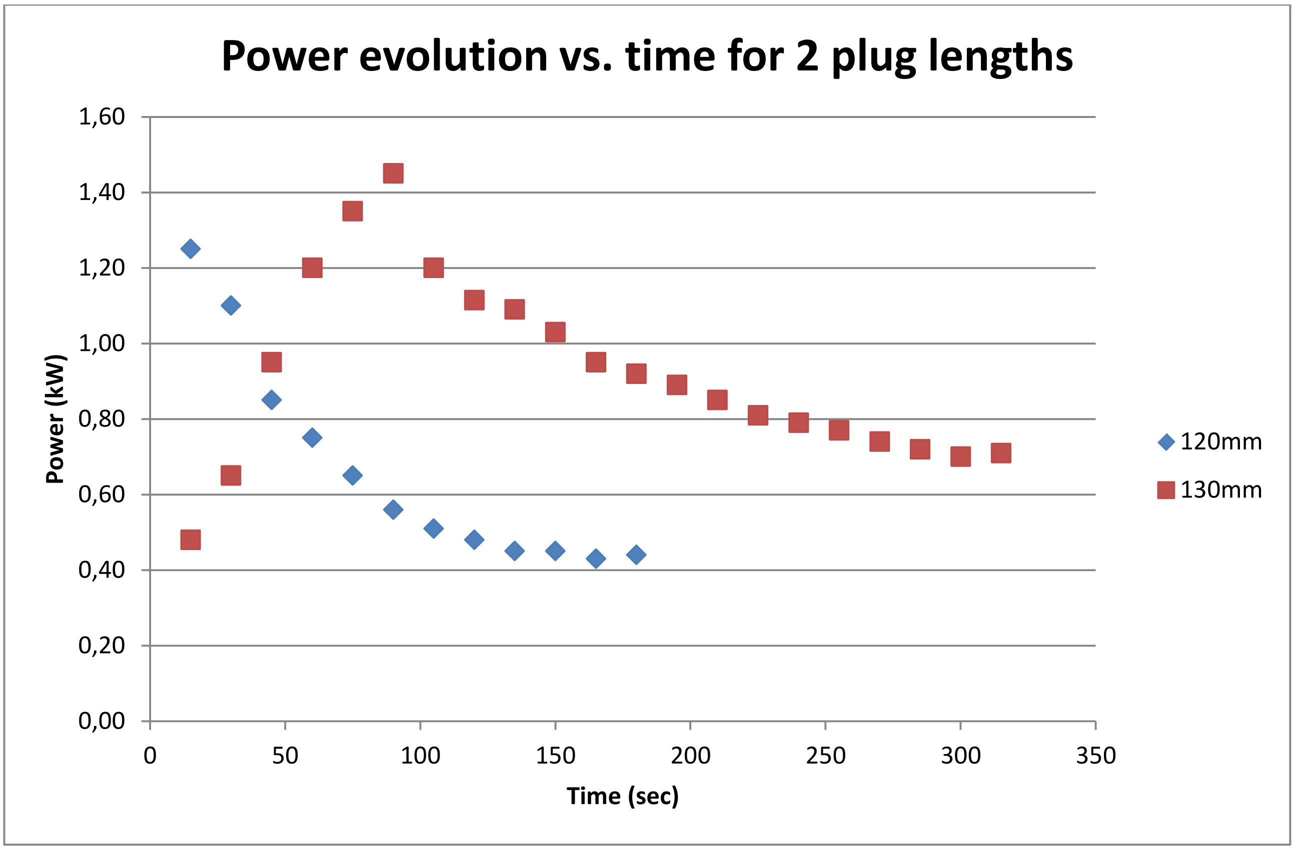


Figure 64 Power consumption vs. time during starting up

A hydraulic system has been mounted on the screw shaft and the manual positioning of the screw is now managed by a PLC.

Based on that, two other solutions have been tried:

- Setup of a load cell at the back of the screw shaft: S-beam load cell able to measure in compression and tension.
- Measurement of pressures in both chambers of the hydraulic piston.

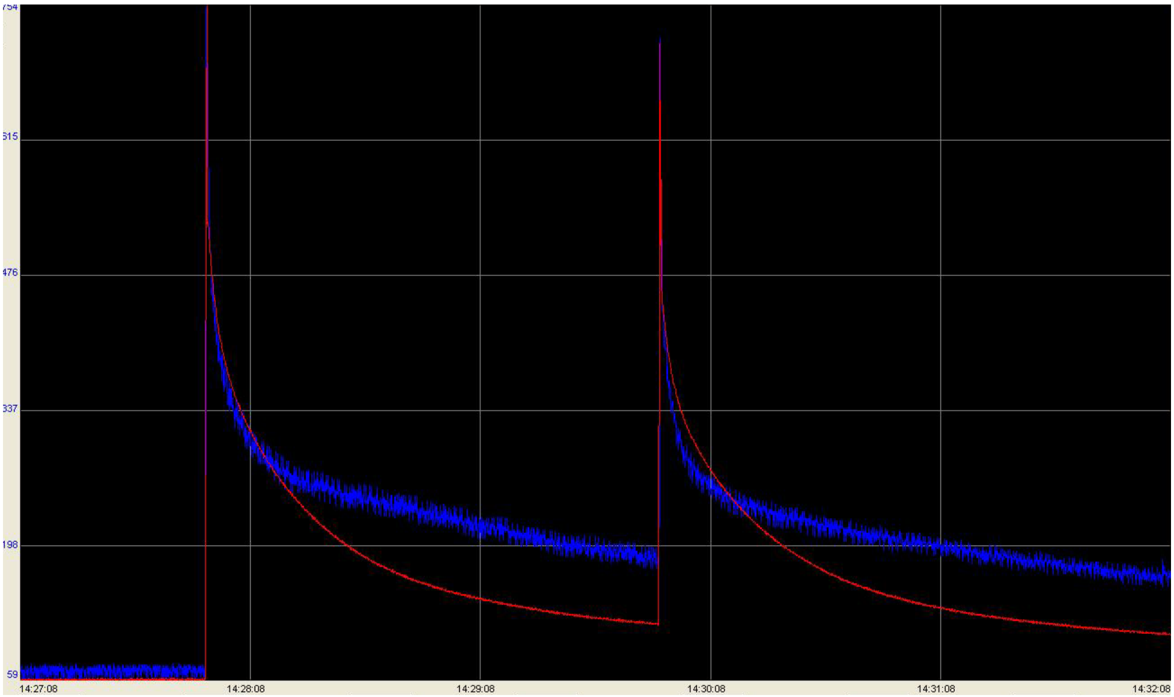


Figure 65 Load cell (red) and hydraulic pressure (blue) responses to a forward movement of the plug screw

Both solutions were working satisfactorily. The hydraulic system has been kept and is used for actuating and measuring. The back pressure gives a good image of the plug hardness.

The system regulates as follows:

- Pressure limits is entered in the PLC
- Pressure at the back of the hydraulic piston is measured
- If the pressure measured exceeds the high limit, the plug screw is moved forward.
  If the pressure measured is lower than the low limit, the plug screw is moved backwards.
- The plug screw is moved during 100 ms. Then, the pressure is checked again after stabilization and the regulation goes on.

With those three main modifications (shaft extension, rubber design and position regulation), the plugging system is working well enough. Test in real conditions will have to be performed in order to validate the principle but the soft plug is expected to handle pressure variations or isolate the dosing screw from back flow.

4.4.6.3. Injection unit

After the finalization of the plugging system, the injection unit has been mounted at its outlet. An extension flange was made in order for the injection system to fit with the extended shaft of the plug screw (see figure 66). An observation window was also mounted on the other side of the injection screw.

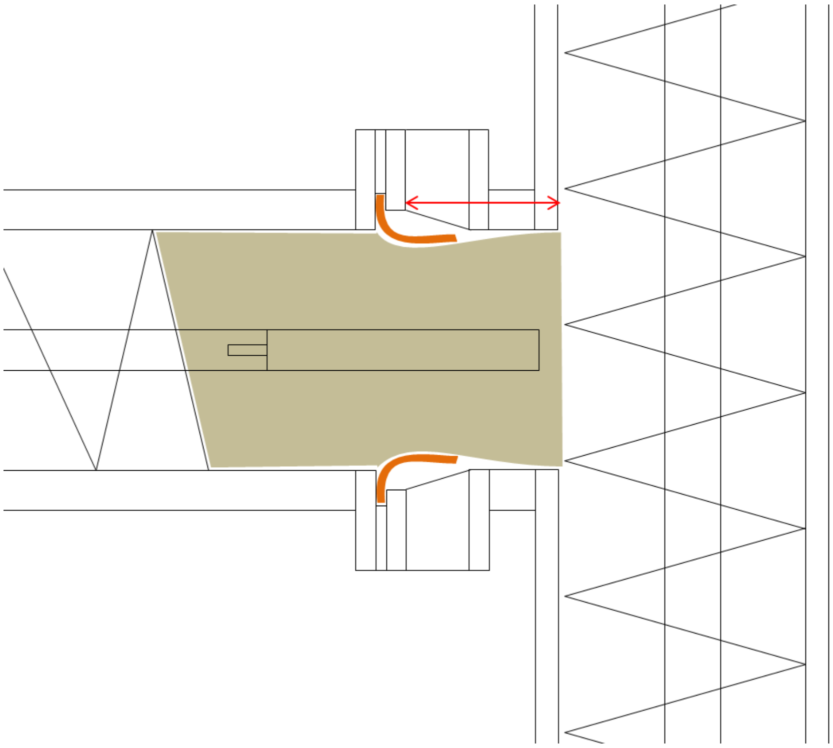


Figure 66 View of the junction between plug screw and injection screw

Primary tests have shown two problems with the injection system:

- The screw flight affects the flow accuracy. Small fluctuations, matching with the screw frequency were detected on the belt conveyor
- The initial velocity (150 rpm at 50 Hz) is too low considering the screw capacity. At high fuel flow, the material is falling by packs of powder.

The figure 67 shows this effect.

Figure 67 "Packs" of powders at the outlet of the injection unit

These two observations could lead to instability of the gasification process. Therefore, a new motor, with a much higher speed (710 rpm at 50 Hz) was installed. The high velocity of the screw results in a smooth and accurate flow of material at the outlet of the injection unit. The two effects observed with the lower velocity motor are not present anymore.

4.4.6.4. Gasification

The cooling system (water storage, water pump, water circuit with flowmeters and valves) has been tested separately and then mounted on the 3 MWth gasifier. Following is a picture of the supply part of the cooling water.

As mentioned in the introduction, the project FLOWGAS was redefined before its end and for this reason the gasifier could not be tested. Oxygen, propane and air supply were not tested either.
TK Energy had however done all the work to the local authorities in order to get the safety authorisations required for installing oxygen and propane supplies and operating them, together with the gasifier.

Figure 68 Picture of the water storage, pump and cooler

5. **Pressurised dosing and injection facility**

The combination of the delivery of the primary dosing bin and the presentation of the work conducted on the FLOWGAS have contributed to TK Energy to get a contract in April 2014, with the French company CEA, for the design and manufacturing of an experimental facility for dosing and injection 50 to 150 kg/h of biomass under pressure at 40 barA.

The facility has been installed and started in Grenoble (France) in July 2015. It is presented hereunder.

5.1. Description

The purpose of this experimental facility is studying the injection of wood powder in a small pipe with help of transport gas. The facility has the function of dosing wood powder at an accurate flow into an injection cone where gas can be injected of different manners. The powder is then transported into a pipe in which pressure is monitored. The powder falls into a bin where the flow can be observe and where the mass flow injected can be measured.

The facility operates up to 40 barA, and has been designed for injecting 50 to 150 kg/h of raw wood powder of a density around 200 kg/m^3. The facility can however be operated with different biomass powders.

The different parts of the facility are described hereunder and the P&I Diagram of the facility follows on figure 69.

The facility consists of the following components:

- a dosing bin
- an injection cone and pipe
- a receiver bin
- two pressurized filters
- a gas system
- a frame
- a control system

5.1.1. Dosing bin

A dosing bin with a volume of 350 L is placed at the top of the facility. The dosing bin is equipped with a bridge breaker that secures a constant filling of the dosing screw. The bridge breaker is also working as a level measurement, as there is a clear correlation between the power consumption and the level of biomass.

A dosing screw in the bottom of the dosing bin is used to dose the biomass to the transport. The transport screw then transports the material to the injection cone. The transport screw can be moved in its axial direction with a linear actuator in order to have the position with the optimum dune in front of the screw.

5.1.2. Injection cone and discharge pipe

The function of the injection cone is to guide the biomass powder into the discharge pipe. The injection cone is equipped with axial and tangential injection of gas to ease the injection of the biomass into the discharge pipe.

The top lid of the cone is also fitted with a thread where a dummy pipe can be mounted for experimentation with a central pipe inside the discharge pipe.

5.1.3. Receiving bin

The biomass powder is conducted into the receiving bin, of a volume of 550 L. This bin is equipped with two windows for the visualization of the discharge tube outlet. The receiving bin has also two blind flanges for future addition of windows.

A weighing bin, located inside the receiving bin and mounted on a load cell, collects and measures the biomass powder flow coming from the discharge pipe. The flow rate is determined by the change in the measured weight.

The receiver bin can be in three height positions corresponding with a discharge pipe length of 1, 2 or 3 meters.

5.1.4. Gas system

The gas system is mounted on the frame, mainly at the first floor of the facility. It includes an inlet part and an outlet part. The inlet part manages the flushing with nitrogen, the pressurization and the gas flow regulation. The outlet part controls the pressure regulation and the depressurization of the system.

The gas system can detect and quantify potential leaks by measuring the gas flow at the inlet and at the outlet of the facility.

5.1.5. Pressurized filters

At the outlet of the receiver bin, the gas system includes a main pressurized filter that collects the biomass particles potentially carried by the gas flow and protects the valves located downstream. In case of emergency stop or clogging of this filter, a secondary line including a clean pressurized filter will be used for a safe depressurization of the system. The clogging of the main filter is monitored by two pressure measurements located before and after the filter.

5.1.6. Frame

The facility is mounted on a frame on two floors. On the first floor, it is possible to access to the injection cone and the gas system. From the first floor, the stairs enable to reach the top platform from which the dosing bin can be loaded with biomass.

5.1.7. Control system

A control system is managed by a Siemens PLC with procedures for

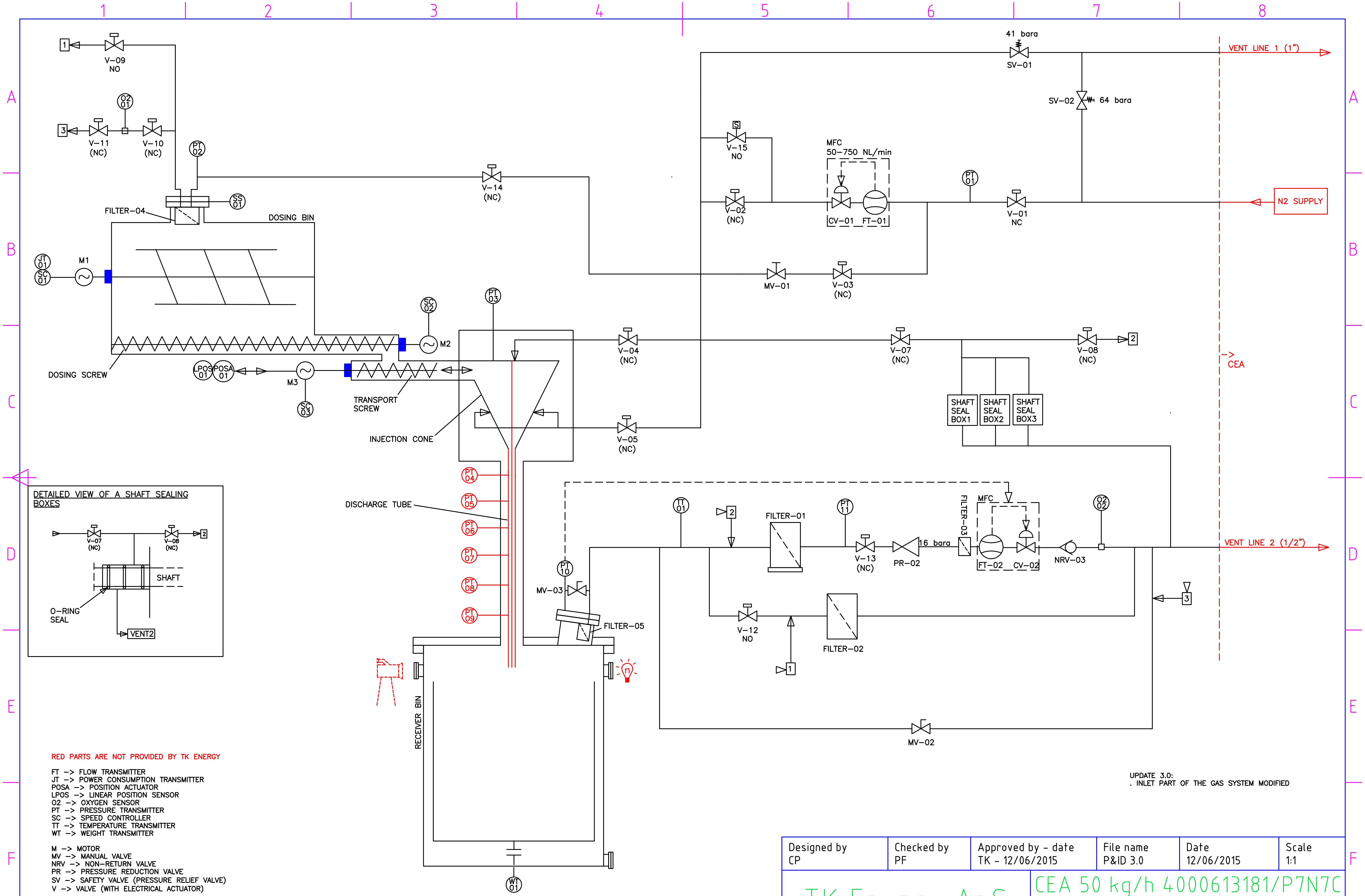
- A full experiment including pressurization, dosing and depressurization
- Safety depressurization and shut down in case of error

- Emergency depressurization in case of critical errors

The system is controlled from a touch screen that can be moved to all the floors. The touch screen provides all information from sensors and displays historical trends, errors and procedure steps.

5.1.8. P&I Diagram

The P&I Diagram is shown next page.



RED PARTS ARE NOT PROVIDED BY TK ENERGY

FT –> FLOW TRANSMITTER
JT –> POWER CONSUMPTION TRANSMITTER
POSA –> POSITION ACTUATOR
LPOS –> LINEAR POSITION SENSOR
O2 –> OXYGEN SENSOR
PT –> PRESSURE TRANSMITTER
SC –> SPEED CONTROLLER
TT –> TEMPERATURE TRANSMITTER
WT –> WEIGHT TRANSMITTER

M –> MOTOR
MV –> MANUAL VALVE
NRV –> NON–RETURN VALVE
PR –> PRESSURE REDUCTION VALVE
SV –> SAFETY VALVE (PRESSURE RELIEF VALVE)
V –> VALVE (WITH ELECTRICAL ACTUATOR)

UPDATE 3.0:
. INLET PART OF THE GAS SYSTEM MODIFIED

Designed by	Checked by	Approved by - date	File name	Date	Scale
CP	PF	TK - 12/06/2015	P&ID 3.0	12/06/2015	1:1

TK Energy ApS

CEA 50 kg/h 4000613181/P7N7C

P&ID 3.0

Sheet
1/1

5.2. Design

The facility is made of 9 different pressure vessels assembled and mounted in a frame. The dimensions of the facility are H 7.3 m x L 2.9 m x W 2.5 m and its weight is 9 tons.
The facility has an operating pressure from 10 to 40 barA for a total volume of 1130 L and operates at ambient temperature.

The following pages contain pictures and drawings of the complete facility and the location of the different pressure vessels.

Figure 70 Picture of the first floor of the facility with the dosing bin and the injection cone vessels

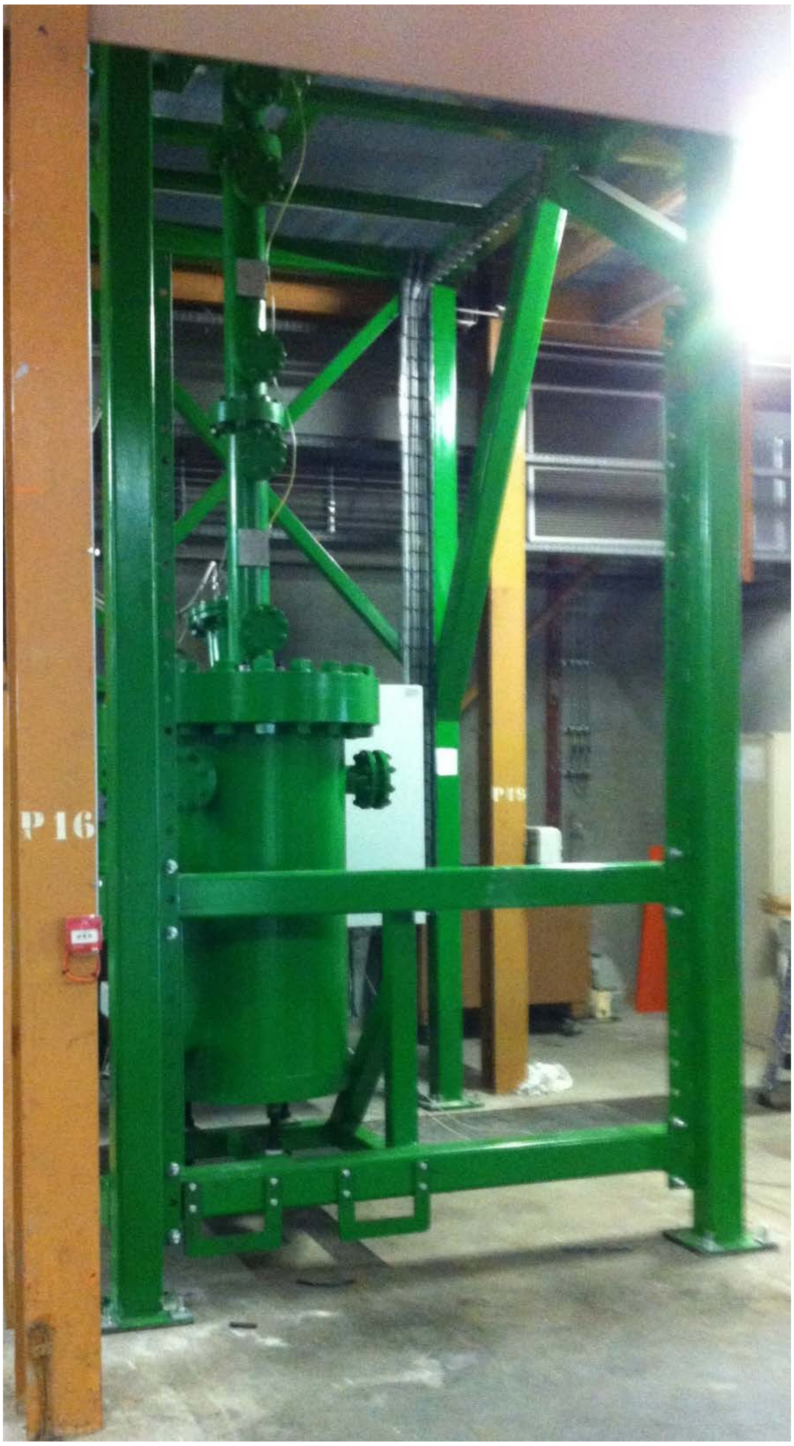
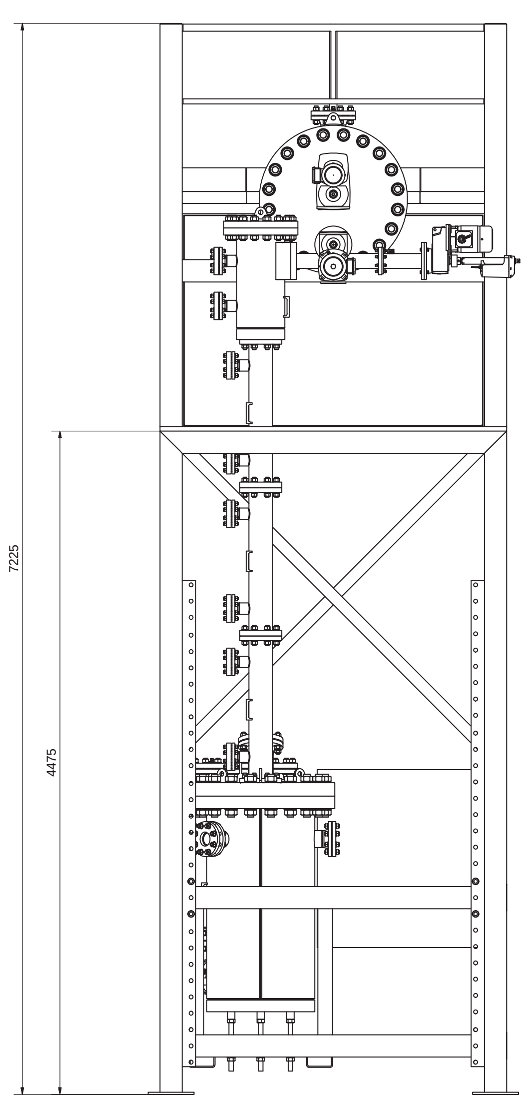
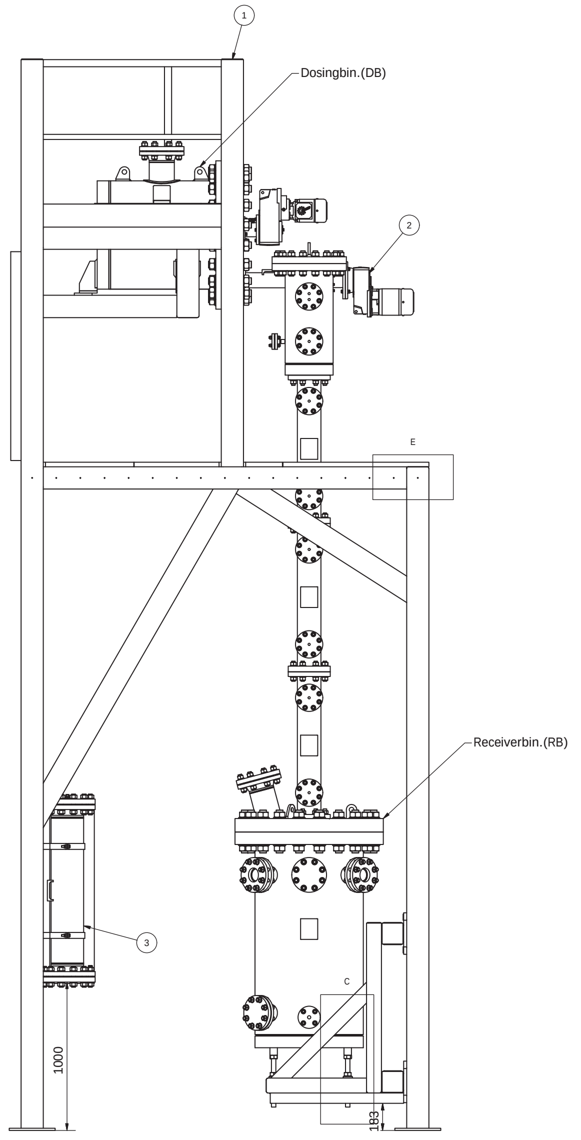
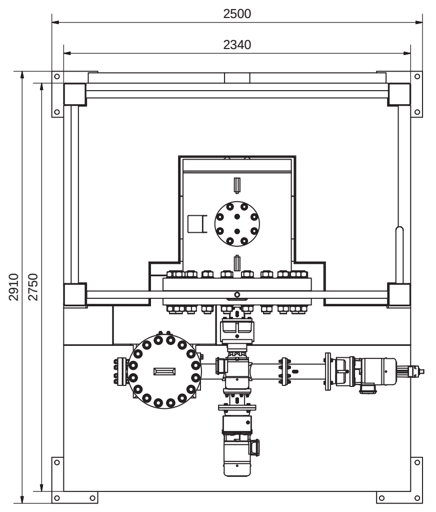


Figure 71 Picture of the ground floor of the facility with the receiver bin

Figure 72 Picture of the gas system







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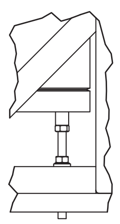

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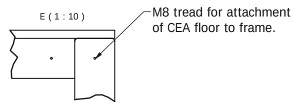

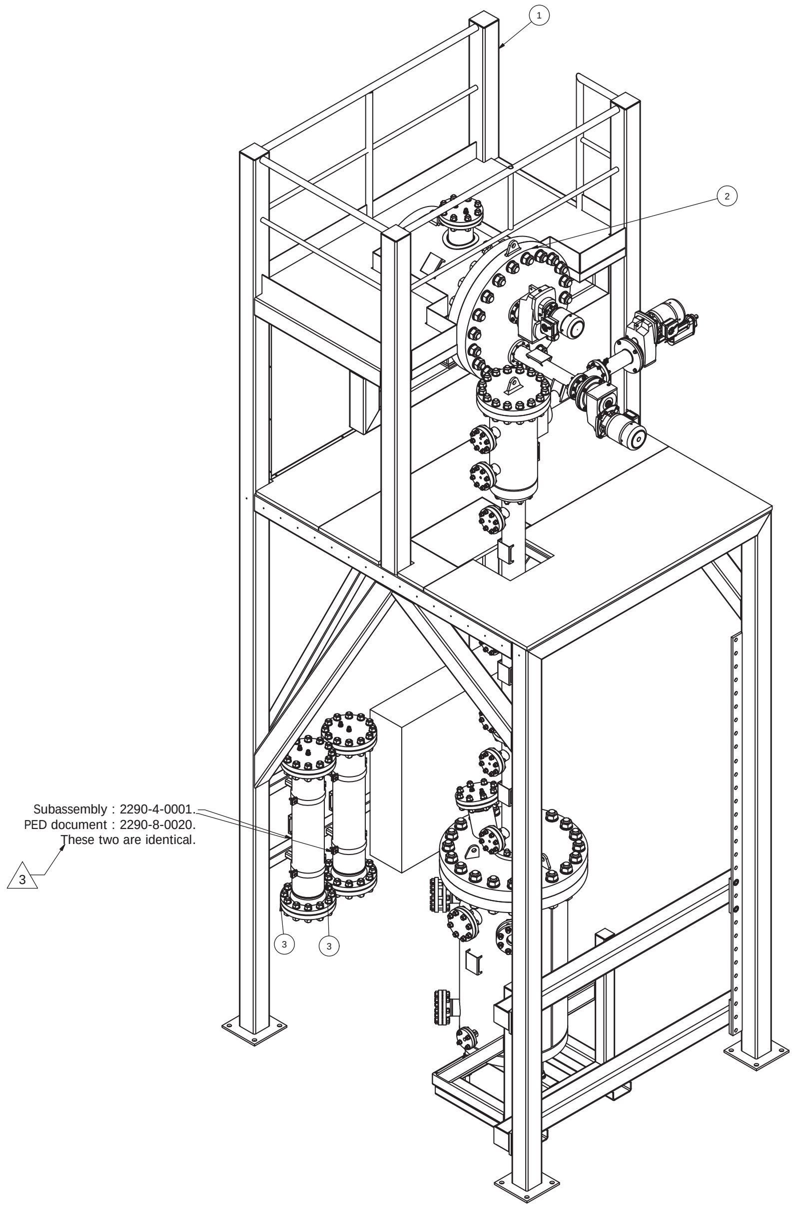

2

PARTS LIST

ITEM	QTY	PART NUMBER	DESCRIPTION	COMMENTS
1	1	Supportframe VS3	See drawing 2290-9-0001	
2	1	CEA_Setup	See drawing 2290-8-0003	
3	2	HPF_Complete VS1	See drawing 2290-4-0001	2 seperate vessels
4	1	switchboard		
5	1	1 floor VS1	See drawing 2290-9-1014	
6	1	1 floor A VS1	See drawing 2290-9-1015	
7	1	1 floor B VS1	See drawing 2290-9-1016	
8	1	1 floor C VS1	See drawing 2290-9-1017	
9	1	2 Floor	See drawing 2290-9-1003	
10	1	Plate f valves	See drawing 2290-8-1023	

REVISION HISTORY

REV	DESCRIPTION	DATE
1		08-08-2014
2	Comments added to partlist	12-08-2014
3	Tekst added	14-08-2014

Title
CEA Teststand VS3

Drawing number
2290-8-0004

Project
4000 613181/P7N7C

TK Energy Aps.
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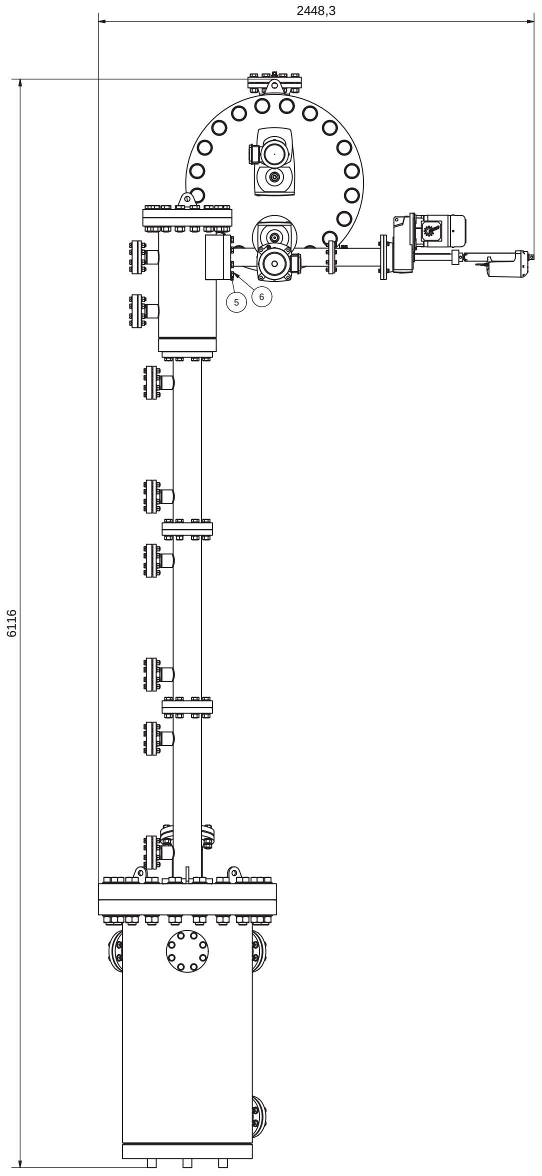
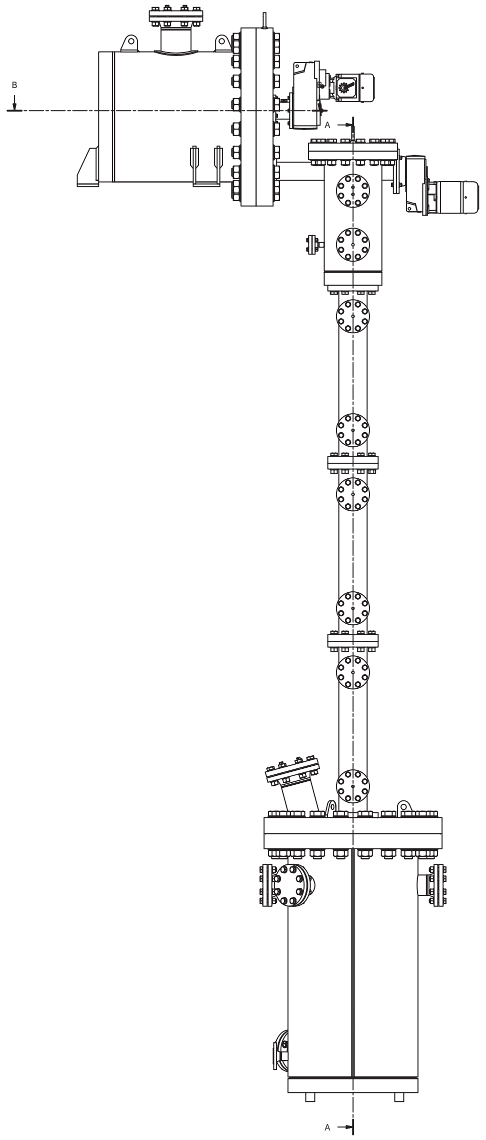
Weight: N/A
Finish:
Scale: 1 : 18
Material:
Designed by: JJN
Checked by:
Approved by:
Date: 27-06-2014

Dimensions without tolerance:
Without decimal: ±0,3
1 decimal: ±0,1
2 decimal: ±0,01
3 decimal: Only CNC.
Not Specified chamfers: Max 0,5
Not specified radius of curvature: Max 0,5
Angle without decimal: ±3°
Angle with 1 decimal: ±1°

A0
1 /1





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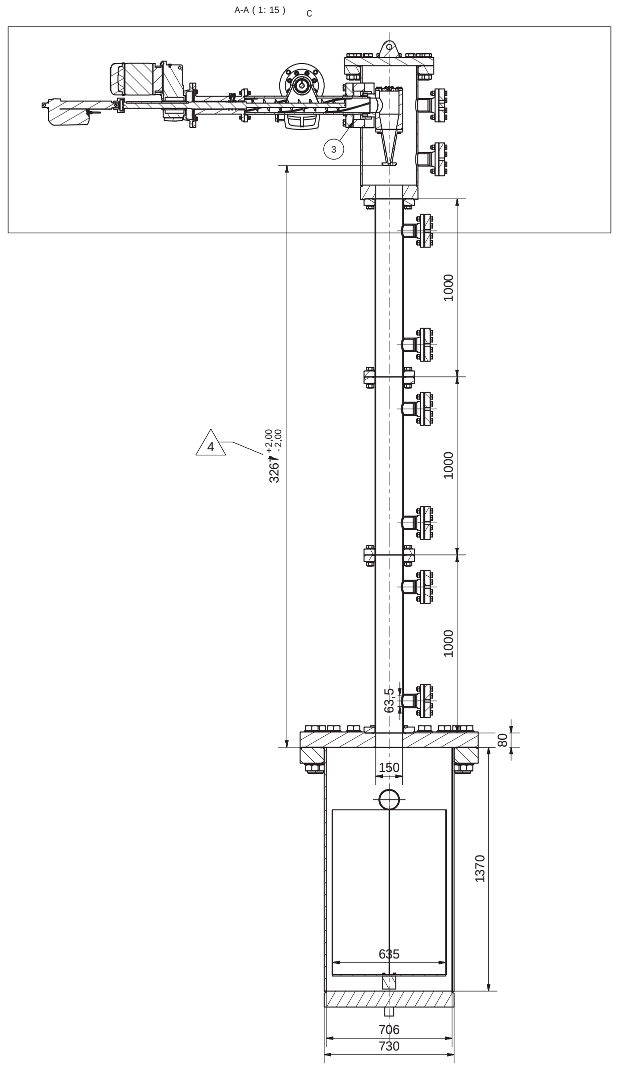

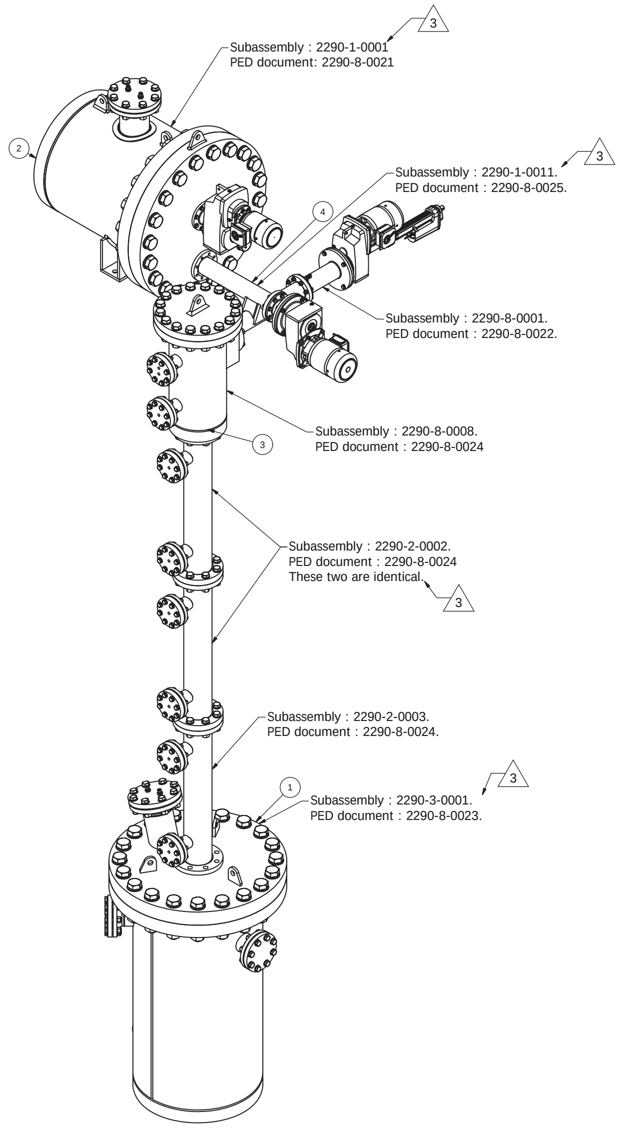

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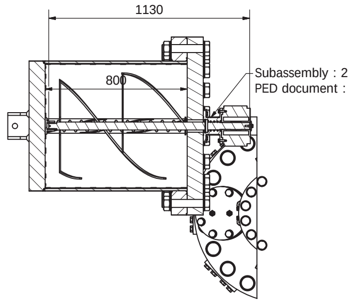

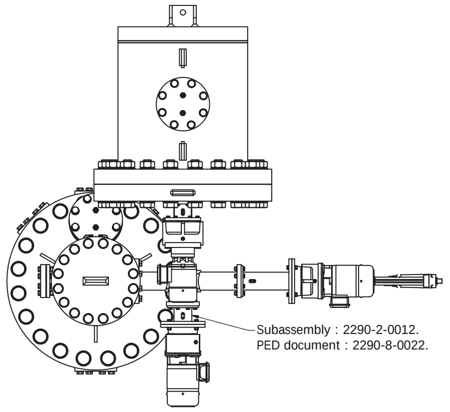

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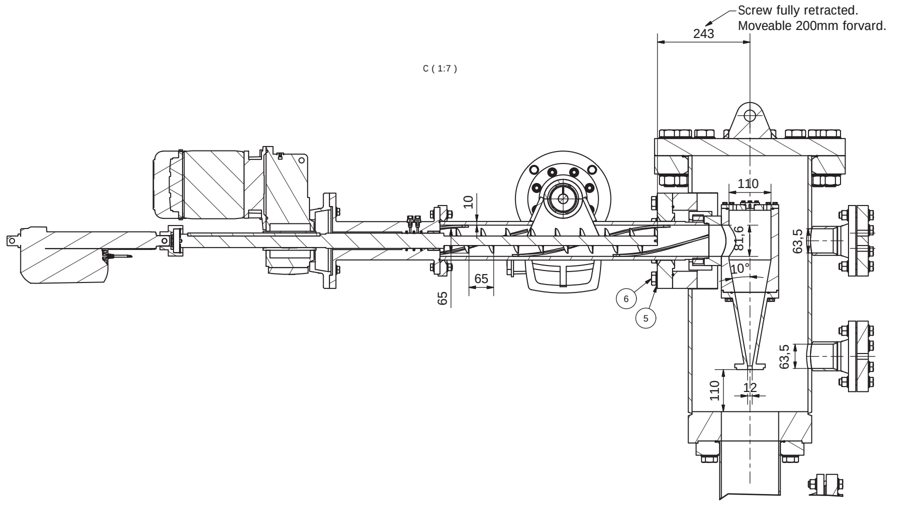

2

PARTS LIST

ITEM	QTY	PART NUMBER	DESCRIPTION	COMMENTS
1	1	RB_Complete VS1	See drawing 2290-3-0001	1 vessel
2	1	DB_Complete VS2	See drawing 2290-1-0001	2 seperat vessels
3	1	IC_Outershell complete	See drawing 2290-8-0006	Contains 4 seperat vessels
4	1	Transition w screws_gears	See drawing 2290-2-0009	Contains 3 seperat vessels
5	8	ISO 7090 - 20 - 140 HV	Plain washers, charmfered - Normal series - Product grade A	
6	8	ISO 4017 - M20 x 70	Hexagon head screws 8.8	

REVISION HISTORY

REV	DESCRIPTION	DATE
1		08-08-2014
2	Comments added to partlist	12-08-2014
3	Subassembly numbers added	14-08-2014
4	Dimensions added	20-10-2014

Title
CEA_Setup

Drawing number
2290-8-0003

Project
4000 613181/P7N7C

TK Energy Aps.
Junkers Industripark
Værftvej 8
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Phone: +45 4618 9000
Fax +45 4618 9018
E-mail: tk@tke.dk

Weight
N/A

Finish

Scale
1: 15

Material

Designed by
JJN

Checked by

Approved by

Date
08-08-2014

Dimensions without tolerance:
Without decimal: ±0,3
1 decimal: ±0,1
2 decimal: ±0,01
3 decimal: Only CNC.

Not Specified chamfers: Max 0,5
Not specified radius of curvature: Max 0,5
Angle without decimal: ±3°
Angle with 1 decimal: ±1°

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5.3. Manufacturing

The facility was designed and manufactured according to the Machine Directive 2006/42/EC as well as the Pressure Equipment Directive 97/23/EC. Considering its pressure and its volume, the equipment was classified in category IV of the Pressure Equipment Directive, resulting in a strict control and approval of each step of the design and manufacturing of the machine.

The design and manufacturing was controlled and approved by the notified body Inspecta. The procedure for getting the approval of the facility was the following.

The project started with the design of the facility. This phase included detailed drawings of the frame, each pressure vessel and their assembly. It included definition of the welding procedures and mechanical calculation.
When finished, the design phase was checked, corrected and approved by Inspecta.

The manufacturing phase started by conducting Welding Procedure Qualification Records (WPQR). In order to be authorized to weld the components, TK Energy had to weld samples according to the 6 different welding procedures defined in the design phase and send them for examination to a specialized welding company (Nordisk Svejse Kontrol A/S). The samples have endured the following tests:

- non-destructive tests
    - visual inspection
    - radiographic examination
    - ultrasonic examination
    - magnetic particle testing
    - penetrant testing
- destructive tests
    - macro examination
    - hardness test
    - tensile test
    - bend test

After approval of the WPQR, the machine could be produced. The quality system of TK Energy had to be improved during this project in order to fulfil the requirements of the directive. For example quality control were reinforced, steel composition was checked and certificates recorded, welding materials were stored in regulated conditions, welding parameters were recorded and steel stamping procedure was elaborated.
TK Energy welders were sent to training courses in order to upgrade their welding certificates as well.

At the end of the production, each pressure vessel has endured non-destructive tests (visual examination, magnetic testing, radiography, ultrasonic and delamination for some of them) and hydrostatic pressure test. Their complete documentations were checked as well.

When assembled, the conformity of the facility and every of its components was checked again.

Everything was double checked by a French notified body working for the customer.

This project and the high requirements of the directives associated have resulted in a real upgrade of the quality management of TK Energy.

5.4. Tests and results

During the debugging and test phase, TK Energy has proceeded to different experiments in order to validate the operation of the dosing technology under pressure.

The biomass powder used during the tests was supply by the customer and is a raw wood powder with a density around 250 kg/m^3.

5.4.1. Atmospheric dosing test

The first test conducted on the facility was the evaluation of the dosing accuracy at atmospheric pressure. Thanks to a conveyor belt positioned at the outlet of the dosing bin, samples of powder were taken at a measured time interval of 0.79 seconds. The samples were weighed and recorded.

The following table and graph show the results of this experiment.

Motor frequency	27.5 Hz	80 Hz
Average mass flow	12.1 g/0.79 s	35.0 g/0.79 s
Standard deviation	1.1 g/0.79 s	2.1 g/0.79 s
Standard deviation	9.3%	6.1%
Average mass flow	55 kg/h	159 kg/h

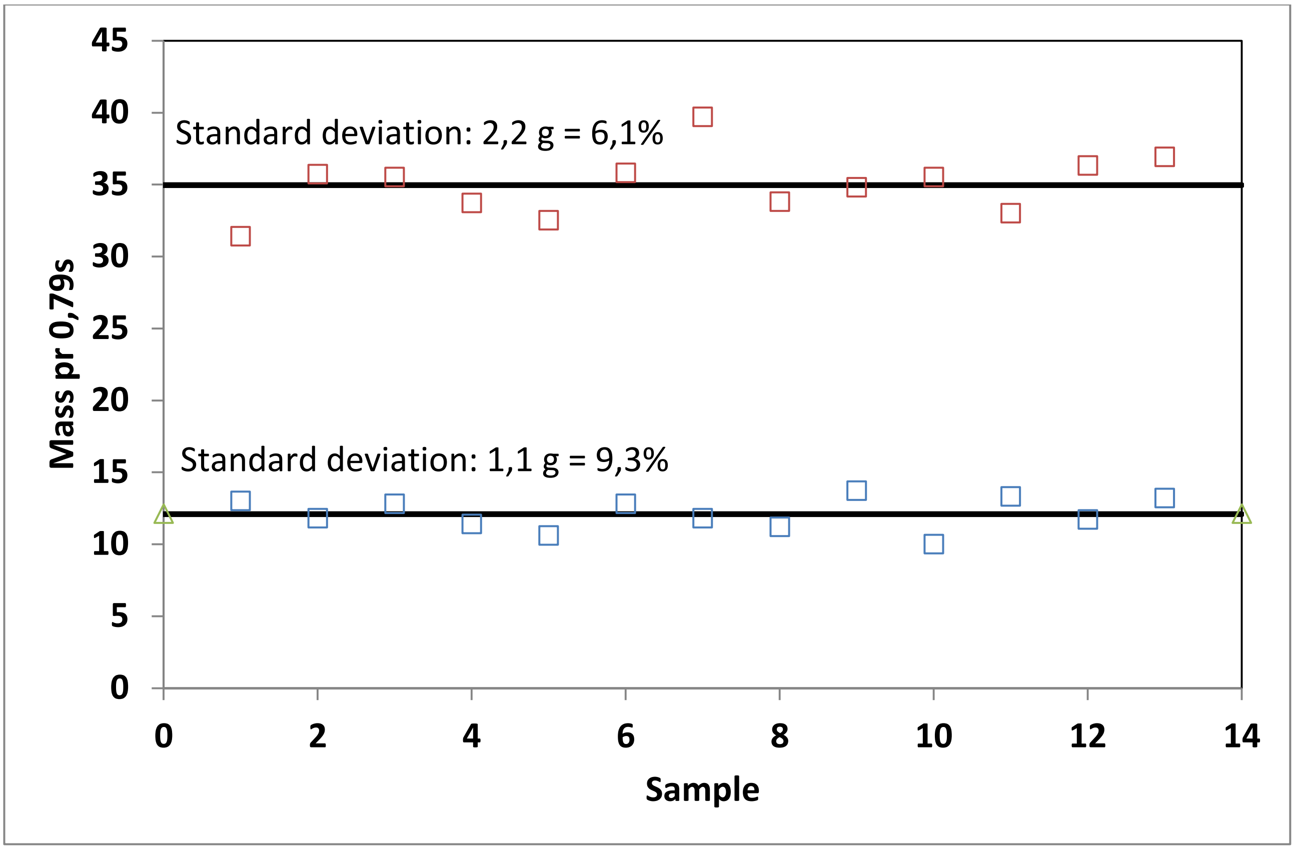


Figure 75 Mass flow accuracy at atmospheric pressure

This experiment shows an acceptable dosing accuracy at atmospheric pressure.

5.4.2. Load cell tests

Inside the receiver bin is present an inner weighing bin which is mounted on a load cell. The powder falls in the weighing bin and the mass measurement gives the possibility to monitor the mass flow. The load cell is a standard single point load cell with a range of 0-100 kg (HBM PW12C3). A special cable entry was manufactured by BARTEC for the connection of the load cell through the pressure outer shell.
The load cell was not guaranteed for operation under pressure but was nevertheless expected to work properly by the manufacturer, therefore validation tests were essential.

The first experiment conducted was an operational and calibration test. The load cell value has been recorded from 0 to 40 barA with different loads: empty / 44 kg / 60 kg. The graph below shows the evolution of the measurements when increasing pressure.

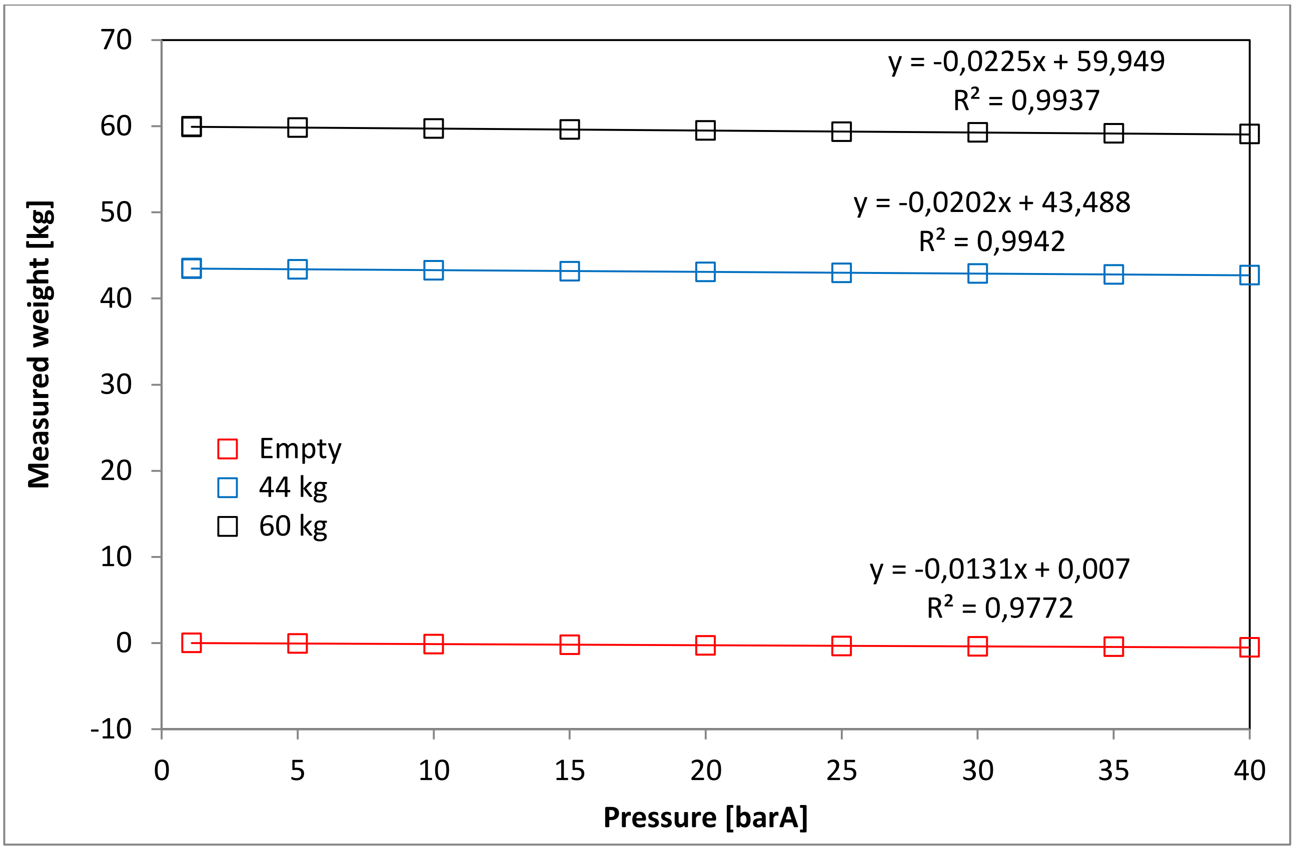


Figure 76 Load cells calibration under pressure

A small decrease (~0.5 kg) can be observed between the measurements at atmospheric pressure and at 40 barA. If an accurate absolute mass value was required, this variation could be problematic but for this specific purpose, an accurate relative mass measurement is interesting for the mass flow calculation.

The second experiment carried out focused on the resolution of the load cell. It was required that the mass measurement system should detect variations lower than 50 grams. In order to conduct such an experiment, an inlet line able to injected small steel balls under pressure was mounted on the lid of the receiver bin. The line consists of two manual quarter turn valves with a Ø 10 mm pipe piece in between:

1. the first valve is opened and the steel balls loaded into the pipe
2. the first valve is closed
3. the second valve is opened and the steel balls fall into the pressurized receiver bin
4. the second valve is closed again

The test was conducted at 35 barA. The steel balls had a diameter of 5 mm and a mass of 0.51 grams. The number of balls introduced and the signal from the load cell were recorded. The results are presented in the following table and graph.

Number of balls	Applied weight g	Weight change g
0	0	0
1	0,5	0
2	1,0	0
3	1,5	2
4	2,0	2
5	2,6	3
6	3,1	3
7	3,6	3
8	4,1	3
9	4,6	3
10	5,1	3
11	5,6	5
12	6,1	7
13	6,6	7
14	7,1	7
15	7,7	7
20	10,2	11
25	12,8	13
30	15,3	16
40	20,4	20
50	25,5	27
70	35,7	35
90	45,9	46
110	56,2	53
130	66,4	64
150	76,6	75

Figure 77 Table of results of the resolution test

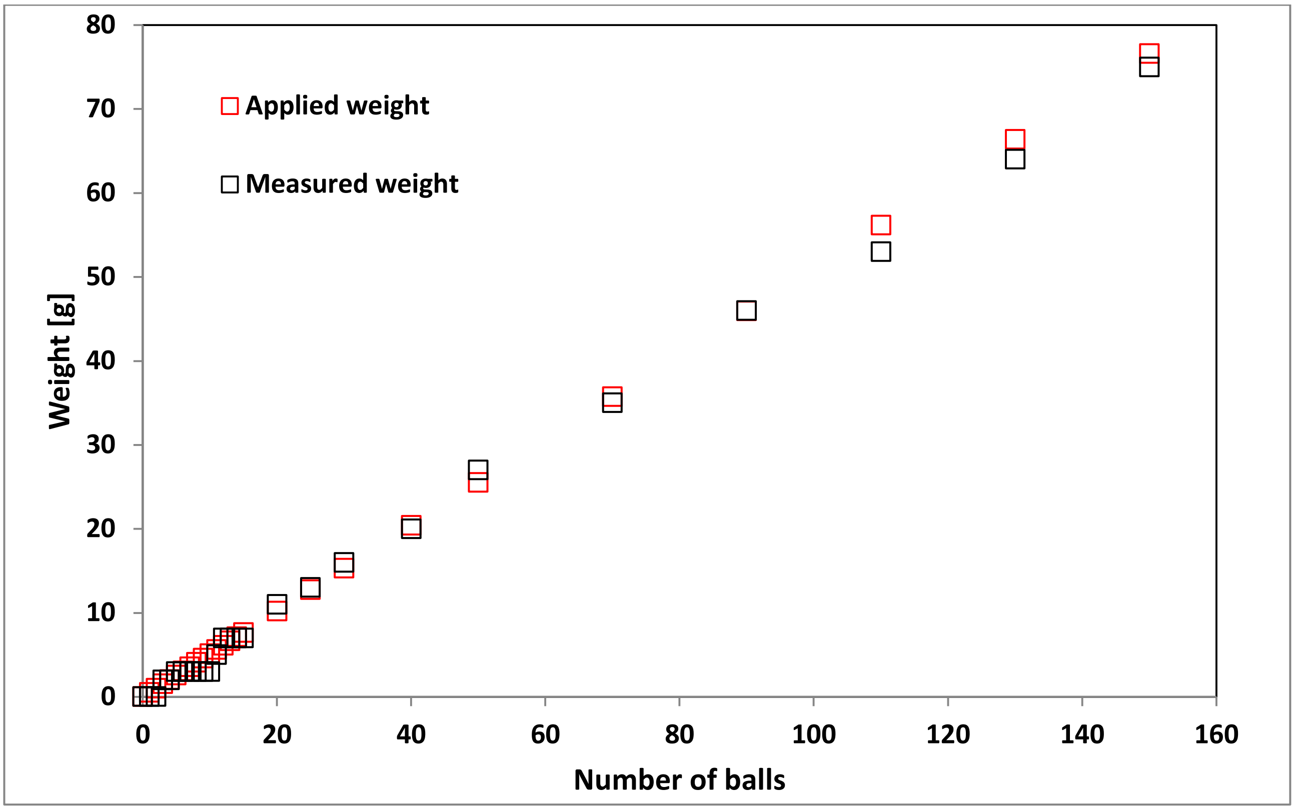


Figure 78 Graph of the load cell resolution test

Changes of 2 grams are detected by the load cell at 35 barA. This resolution is much better than the specification required.

These two experiments have shown a very satisfactorily behaviour of the load cell under pressure. Both accuracy and resolution are good enough and this solution constitute a simple and cheap solution for measuring mass under pressure.

5.4.3. Pressurized dosing experiment

The final experimental tests were done at the highest pressure 40 barA with injection of wood powder from the dosing bin down to the receiver bin. A flow of nitrogen was injected into the facility in order to maintain the pressure in the dosing bin; as powder is removed from the dosing bin, the volume has to be replaced by pressurised gas.

A gas flow of 50 NL/min was used at low biomass flow (<50 kg/h) whereas at higher biomass flow (150-200 kg/h), the gas flow was increased over 400 NL/min. The gas injection had however no effect on the biomass flow as the discharge pipe used for the experiments had an inner diameter of 80 mm.

The first graph shows the evolution of the mass in the weighing bin versus time for wood powder mass flow under 50 kg/h. This value is the minimal flow on which the facility is intended to be used and is also the worst case regarding dosing accuracy. The specification required was a dosing accuracy within +/- 5% of the flowrate over 5 minutes.

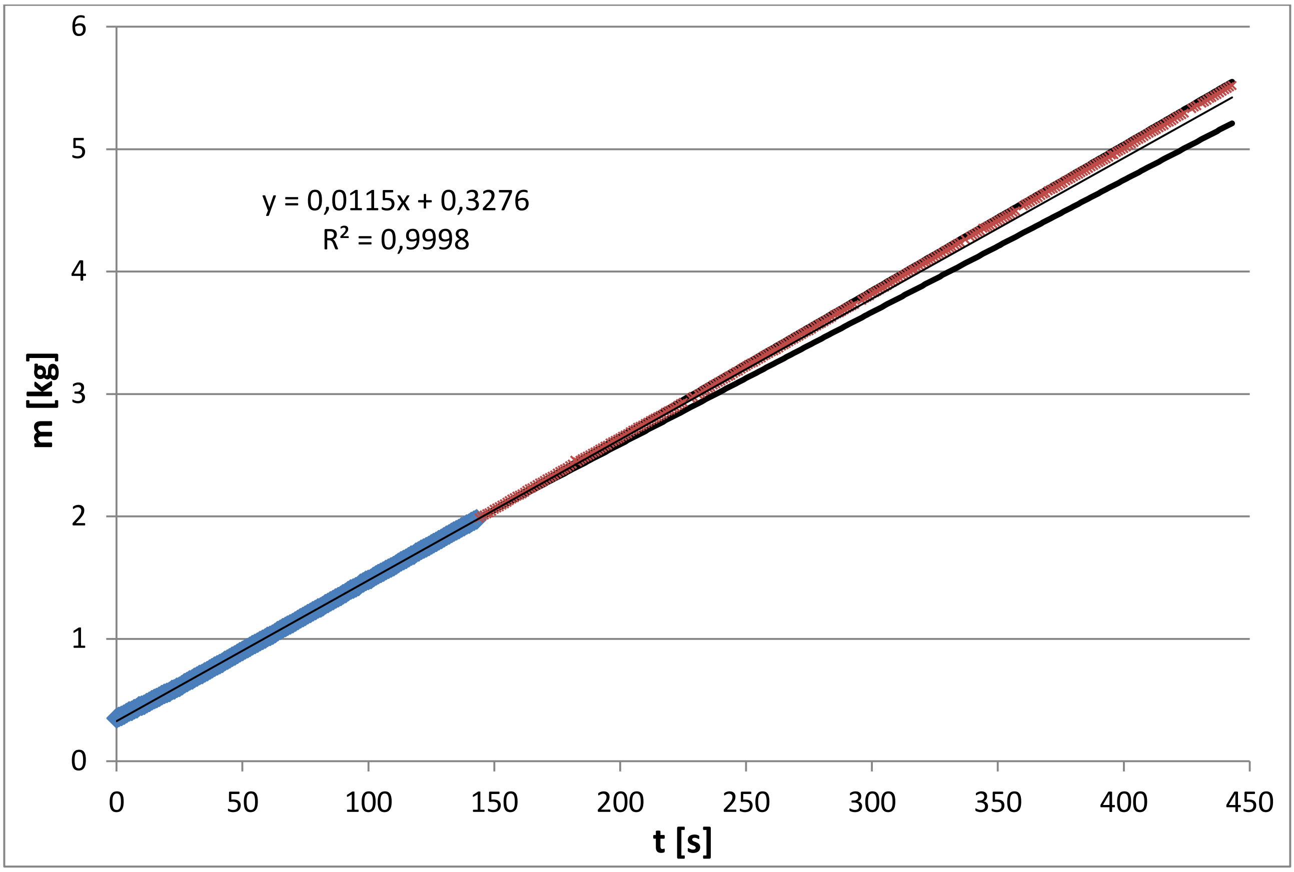


Figure 79 Graph of the mass evolution dosed at 40 barA

The test was held in two parts:

- A first part of 140 seconds where the mass was simply measured (blue markers) and an average of the mass flow was calculated and taken as reference
- A second part of 300 seconds where the mass was monitored (red markers) and compared to the mass calculation with either plus or minus 5% of deviation in flowrate (black lines)

The mass flow average is 41.4 kg/h. The conclusion regarding this experiment is that the dosing accuracy is within the limits +/- 5%.

A dosing test was also conducted at higher biomass flow rate (>200 kg/h) and is shown on the next figure.

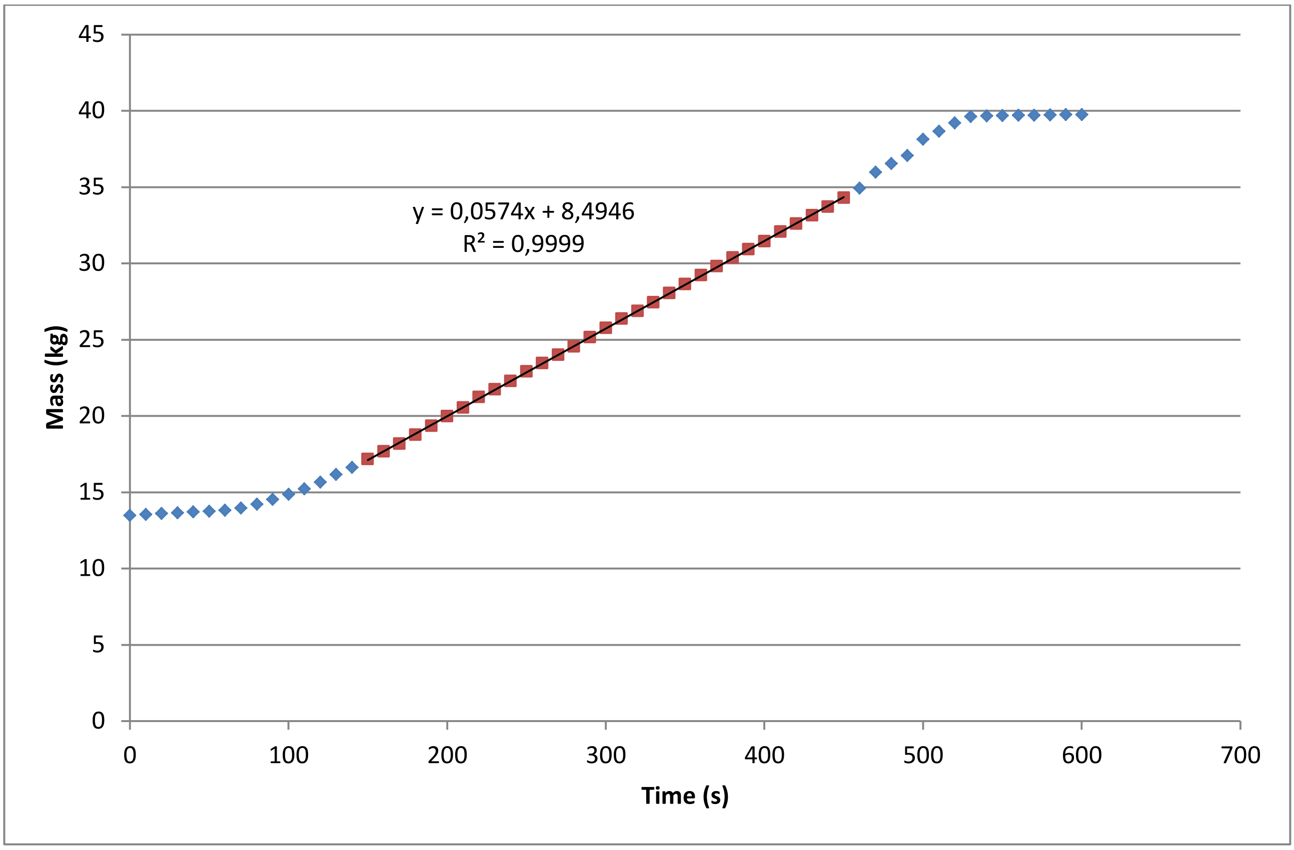


Figure 80 Graph of maximum biomass mass flow at 40 barA

The first and last part of the graph, in blue, show the starting phase and the stopping phase where the dosing bin gets empty and therefore are not stable. In between, a very stable dosing is observed. The mass flowrate is 206.6 kg/h.

5.4.4. Flow observation

The receiver bin is equipped with two observation windows. There are placed on the upper part of the vessel and give the possibility to observe the flow of powder exiting the discharge pipe. It is very interesting to observe the difference of behaviour between atmospheric and pressurised conditions. The higher density of the gas results in a much slower fall of the powder than in atmospheric conditions. The flow is also more turbulent under pressure.

The first picture of figure 81 is taken with atmospheric pressure inside the receiver bin. The powder is falling at high speed and straight to the bottom of the vessel. The picture is not very clear because the powder contains a lot of micrometric particles that fly after falling in the weighing bin. This phenomenon is not observed at high pressure, as shown on the second picture of figure 81. The picture is clearer because the particles rest at the bottom of the bin and do not fly because of the high gas density. The turbulences can be observed as well.

Figure 81 Pictures of wood powder injection into atmospheric and pressurized vessels

6. **Sludge dryer**

As previously mentioned in this report, the FLOWGAS project was redefined in April 2015 and the remaining budget has been reinvested in the development of a sludge dryer. There is an important market in treatment and valorisation of sewage sludge and direct potential customers in the Køge area. The development of an efficient dryer is the first step towards gasification of this low quality fuel and was not included in the initial FLOWGAS project. In this way, TK Energy head towards a complete feeding line from wet low quality fuel to injection in a gasifier.

TK Energy has therefore focused on the design of a 1 kg/s dryer of wet sewage sludge dryer in the last part of the FLOWGAS project. The dryer is intended to take wet sewage sludge with a moisture content around 75 % and deliver dry sludge with a moisture content down to 10%. The inlet flow of 1 kg/s is based on the scale of the EUDP Project 10 MW Pressurized Entrained Flow Gasification granted in 2014 and in which TK Energy conducts an engineering phase for the development and demonstration of this gasification technology.

6.1. Principle

The technology developed is drying the wet material in a steam atmosphere. The dryer is gas tight and after heating up phase, it is operated at a steam pressure of 1.05 barA and a temperature of 120°C.

The control of the pressure is done by a condenser. The condenser is connected to the dryer and is supplied with “cold” (65°C) water. By increasing the inlet flow of water going through the condenser, more steam is condensed resulting in a lowering of the pressure. This will result in a flow of steam going from the dryer to the condenser: the pressure will be kept at 1.05 barA in the dryer and the water evaporated from the wet material will be evacuated to the condenser. This regulation can be done by a control valve on the condenser inlet line and a pressure measurement in the dryer.

The dryer is heated by circulation of hot water in drying plates on which the material will be moved. The water circulates in the heating loop at a pressure of 4 barG and a temperature of 130°C. The temperature in the dryer is controlled by the flowrate of hot water going through the drying plates. In order to avoid condensation of the steam inside the dryer, the temperature is regulated at 120°C.

The material is spread on a drying plate in a layer of thickness between 100 and 300 mm. Scrappers moves the material on top of the plate until its end where the material falls on another drying plate. It is expected to have 20 drying plates. It is difficult to estimate the residence time of the material in the dryer as the heat transfer between the drying plate and the material cannot be accurately modelled. The residence time required will be determined by preliminary experiments from which travel speed of the scrappers and thickness of material layer will be defined. A residence time between 5 and 20 hours is expected.

6.2. Design

Two different designs are considered for the construction of the dryer. The differences between the two designs concern mainly the frame construction whereas the inner components are quite similar.

Both constructions are equipped with drying plates containing hot water channels. The channels supply heat to the drying process. The sludge is moved by scrappers that are assembled together and are pulled by strong chains. The system is driven by a hydraulic system. One assembly of scrappers, chains and hydraulic system moves sludge on two drying plates as illustrated on the sketch underneath.

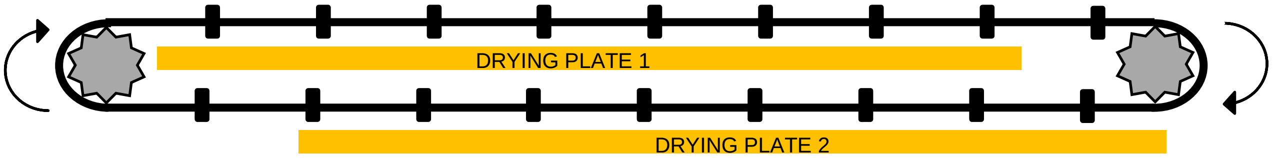


Figure 82 A pair of drying plate and the scrappers

Design 1

The first design consists of a big frame made of HEB beams. Inside this frame are mounted 20 drying plates equipped with scrappers, chains and hydraulic system.

The frame is closed by an inner shell that has the function of keeping the dryer gas tight and its inert steam atmosphere. The inner shell is made of steel plates directly mounted on the frame and sealed with silicone.

Around the inner shell is a thermal isolation layer reducing the heat losses of the system. The isolation layer is protected by a thin steel outer shell.

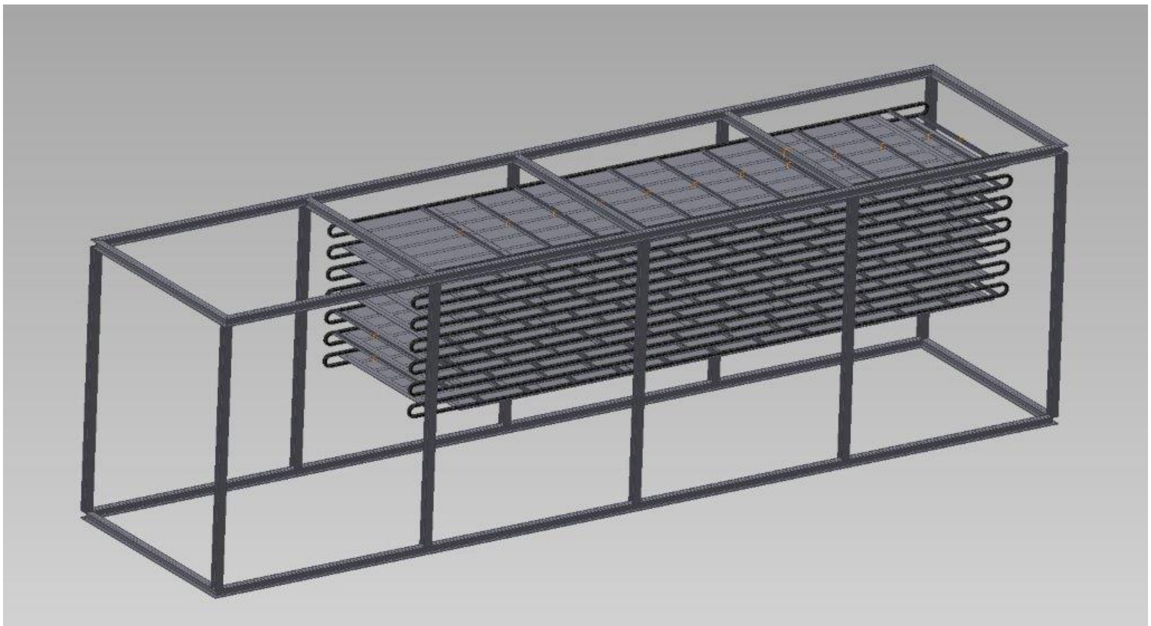
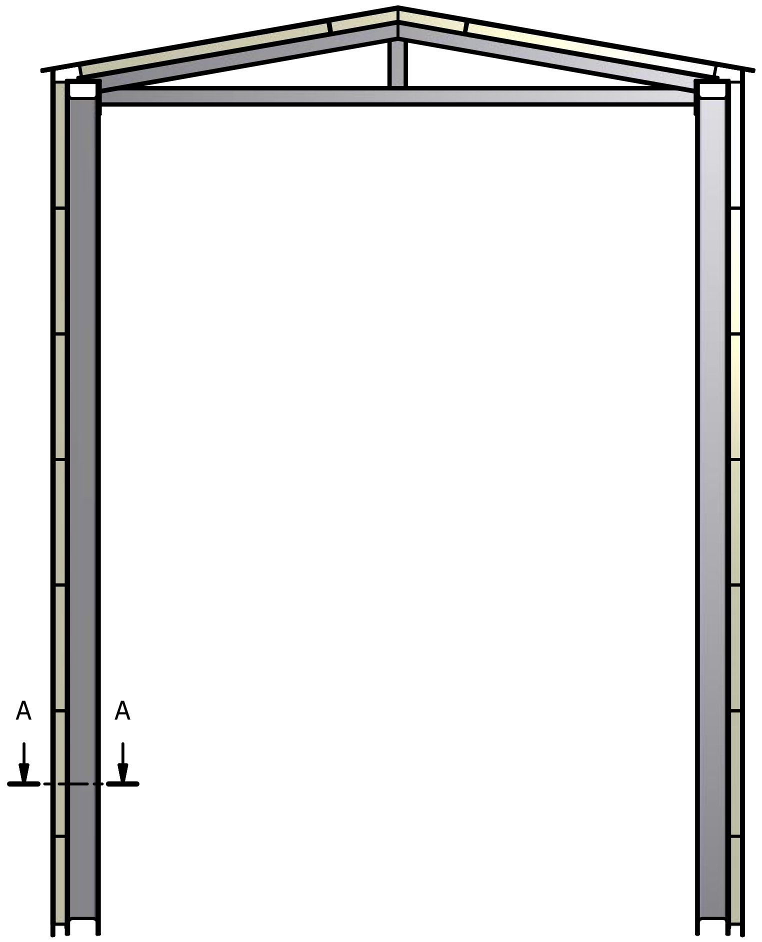


Figure 83 Overview of the construction design 1



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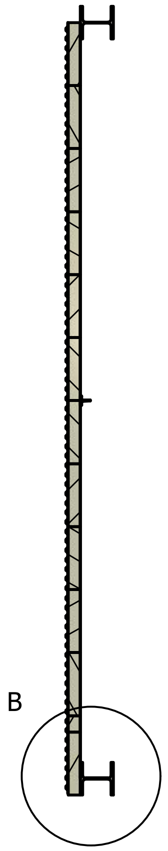
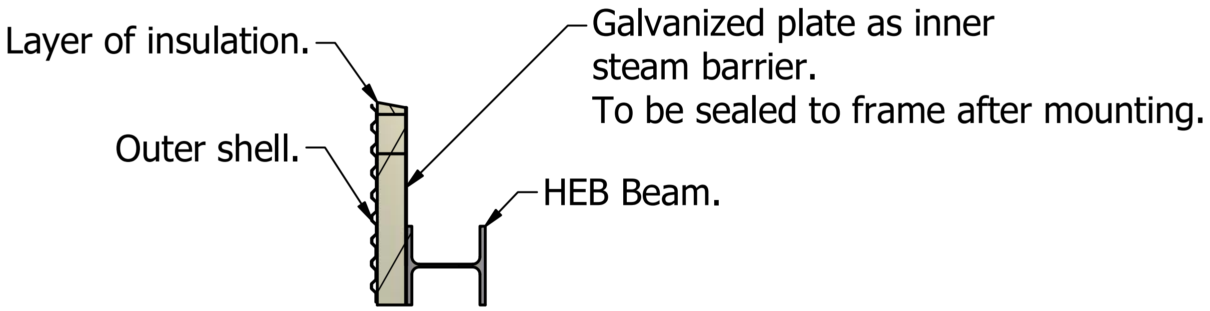
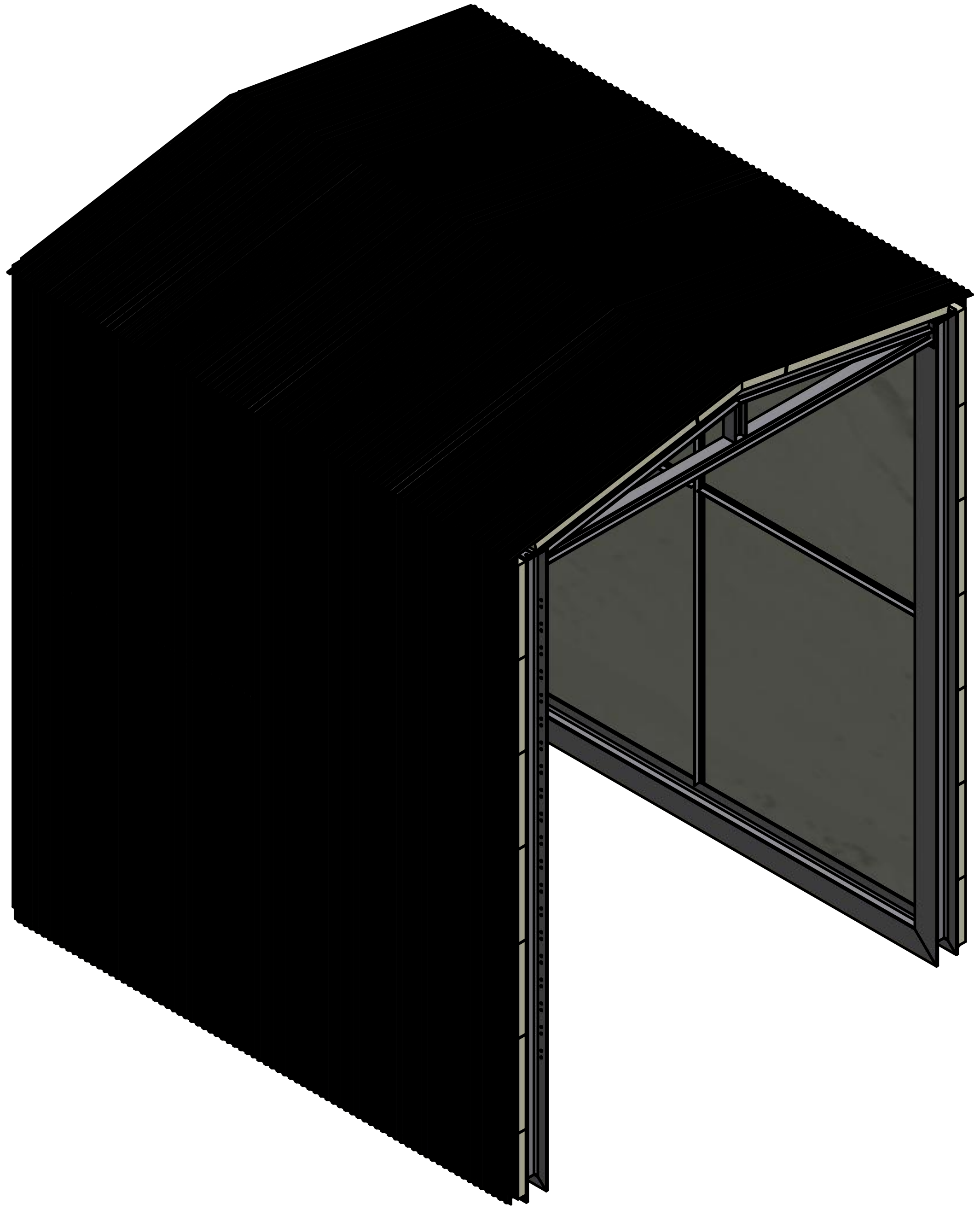


B (1 : 25)





Drawing number

Title
Modul 1 complete

Project

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Weight	Finish		Scale	Material
Designed by JJN	Checked by	Approved by	Date 04-09-2015	

Dimensions without tolerance:
Without decimal: ±0,3
1 decimal: ±0,1
2 decimal: ±0,01
3 decimal: Only CNC.
Not Specified chamfers: Max 0,5
Not specified radius of curvature: Max 0,5
Angle without decimal: ±3°
Angle with 1 decimal: ±1°

A3

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Design 2

The second design is built of smaller frames assembled together. Each frame unit is made of UNP beams and contains a set of 2 drying plates equipped with scrappers, chains and hydraulic system. The drying plates are directly welded on the frame.
This dryer is then an assembly of 10 units containing each 2 drying plates. The units are bolted together on top of each other.
With this design, the frame units are also the inner shell, keeping the steam atmosphere inside the dryer. Rubber seals will be squeezed in between the frames for sealing.
As the first design, an isolation layer is also placed around the construction for reducing the heat losses of the system and is covered by a thin steel outer shell as well.
The assembly is mounted on an isolated foundation.

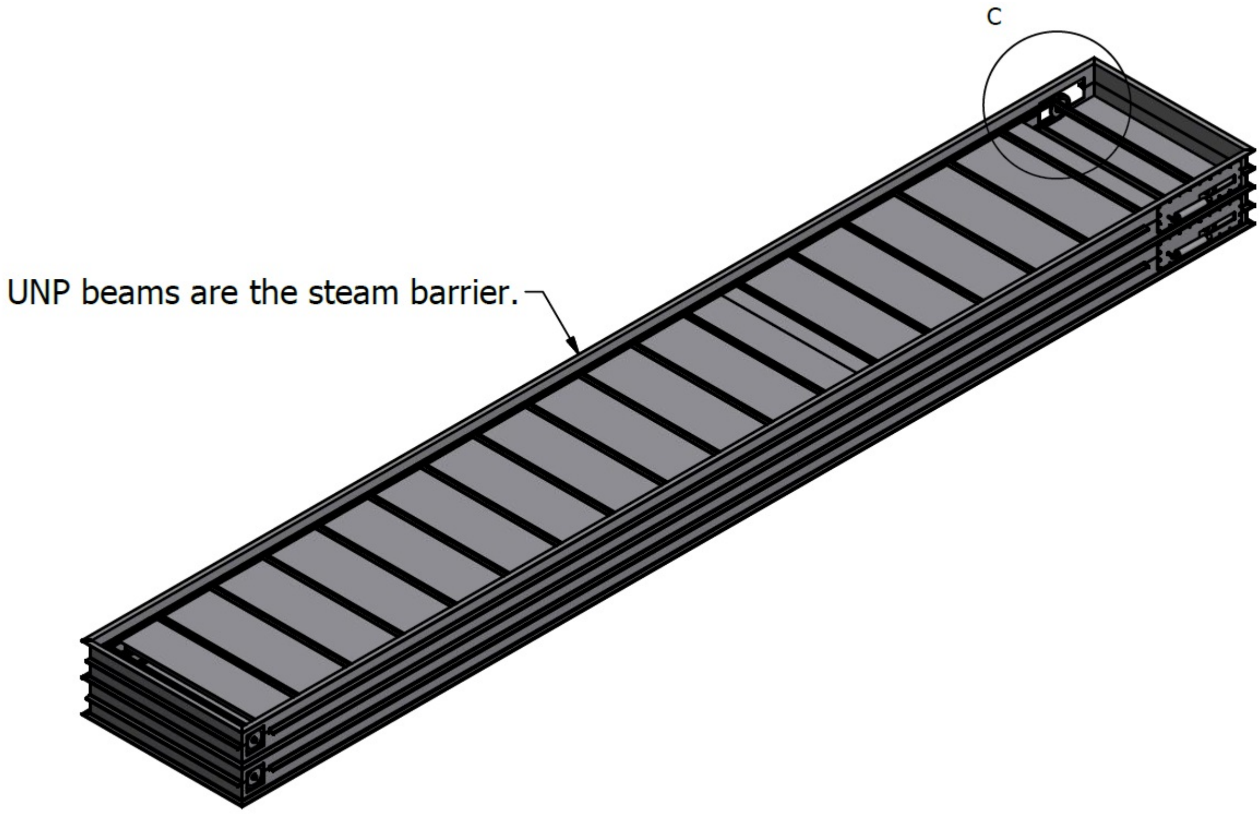
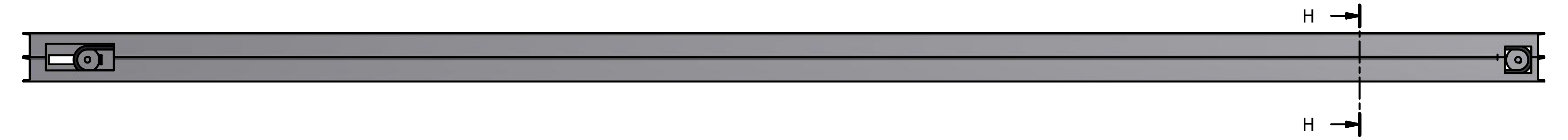


Figure 85 Sketch of the construction design 2



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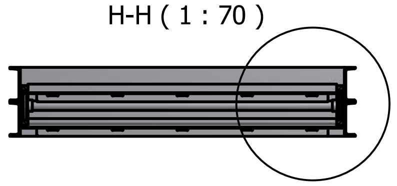

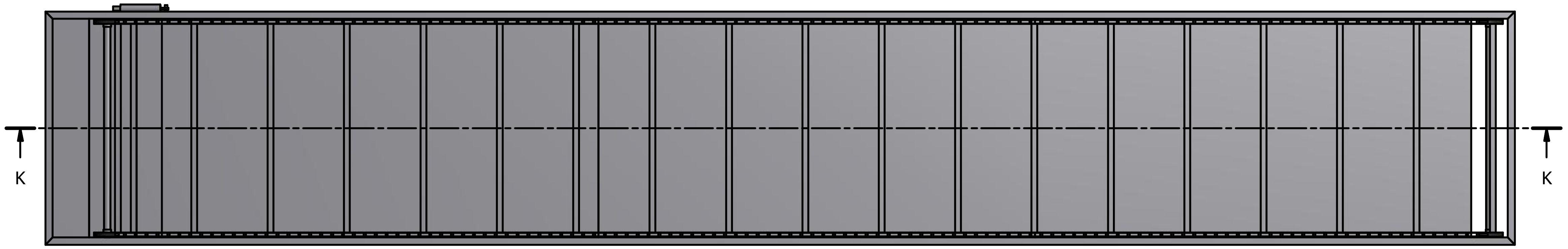

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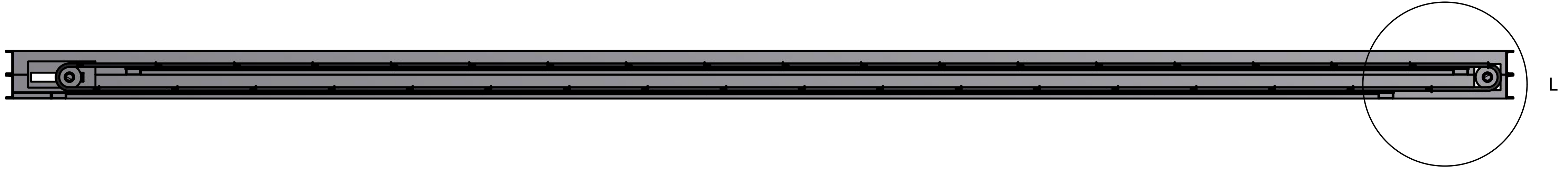
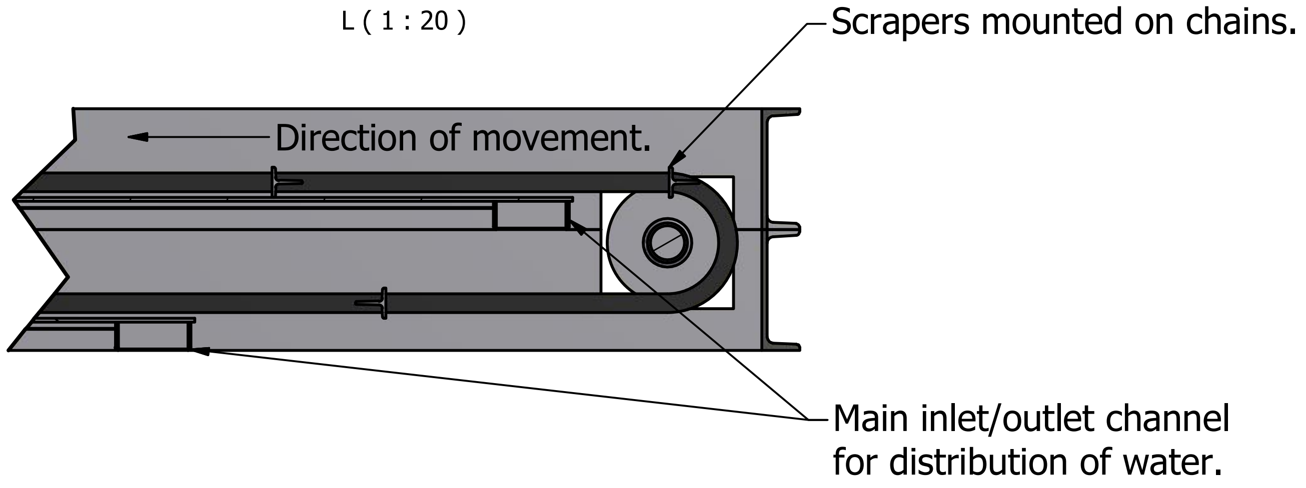


L (1 : 20)



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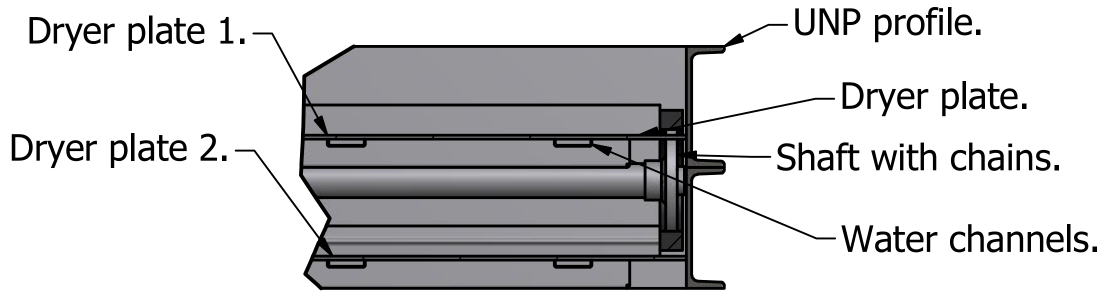


Drawing number					TK Energy Aps. Junkers Industripark Værftvej 8 4600 DK-Køge Phone: +45 4618 9000 Fax +45 4618 9018 E-mail: tk@tke.dk
Title **4 plader samlet**			Project		
Weight N/A	Finish		Scale 1 : 100	Material	
Designed by JJN	Checked by	Approved by	Date 25-06-2015	**Dimensions without tolerance:** Without decimal: ±0,3 1 decimal: ±0,1 2 decimal: ±0,01 3 decimal: Only CNC.	Not Specified chamfers: Max 0,5 Not specified radius of curvature: Max 0,5 Angle without decimal: ±3° Angle with 1 decimal: ±1°

A3

3 /3

The table below gives an overview of the advantages and downsides of each design.

	+	-
Design 1	• Easy access for maintenance • Possibility of placing a downsizer in the same frame and its inert steam atmosphere	• Bigger volume resulting in a longer starting up phase and bigger heat losses • Construction more difficult (mounting of drying plates)
Design 2	• Compact construction • The frame has the double function of supporting and sealing	• Difficult access for maintenance to the lower parts of the dryer • Sealing between the frame units might be difficult

Figure 87 Table of comparison of the two dryer construction designs

The decision concerning the construction design has not been taken yet.

6.3. Drying plates

Several designs of drying plates are considered. The parameters taken into consideration for the selection of the drying plate design are the following:

- Weight and size
- Difficulty of construction (especially regarding welding)
- Difficulty of meeting the requirements of the Pressure Equipment Directive 97/23/EC

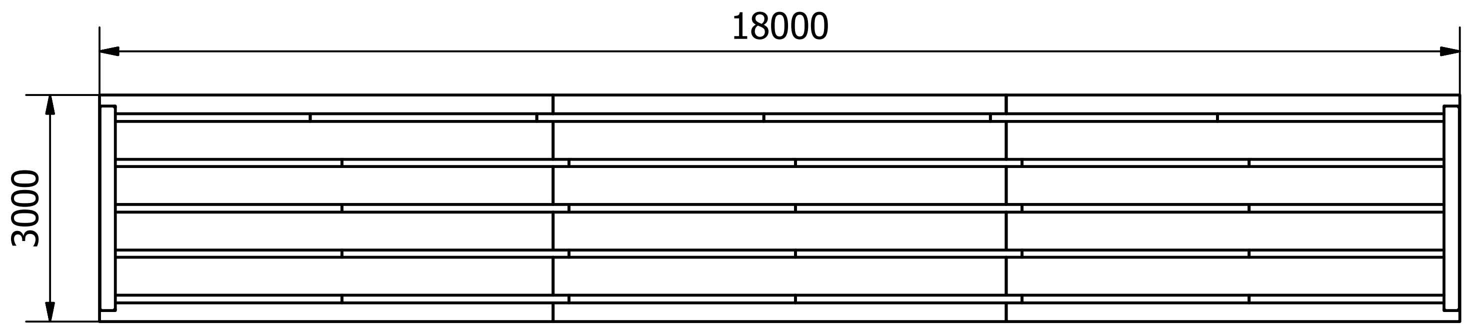
Three drying plate designs have been selected as potential solutions. There are presented hereunder.

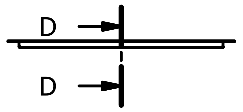
Solution 1

A first solution is the welding of rectangular water channels on the bottom of a 10 mm thick steel plate. The rectangular channels are made of bended plate.

Figure 88 Sketch of the first drying plate solution

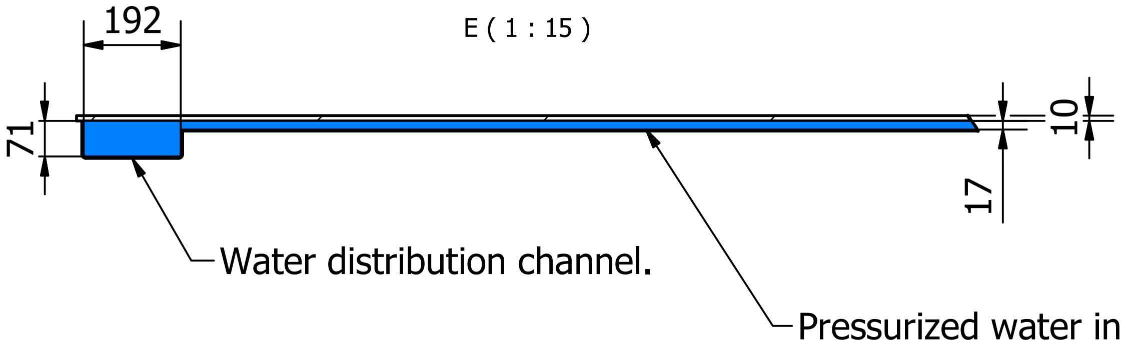
The main advantage of this design is the possibility of having a big exchange surface area without having deep channels. It is a compact solution and can transfer a lot of heat to the drying plate.
On the downside, there is a high quantity of high quality welding required which must be controlled to meet the requirements of the Pressure Equipment Directive. The rectangular shape could also be problematic regarding this Directive.

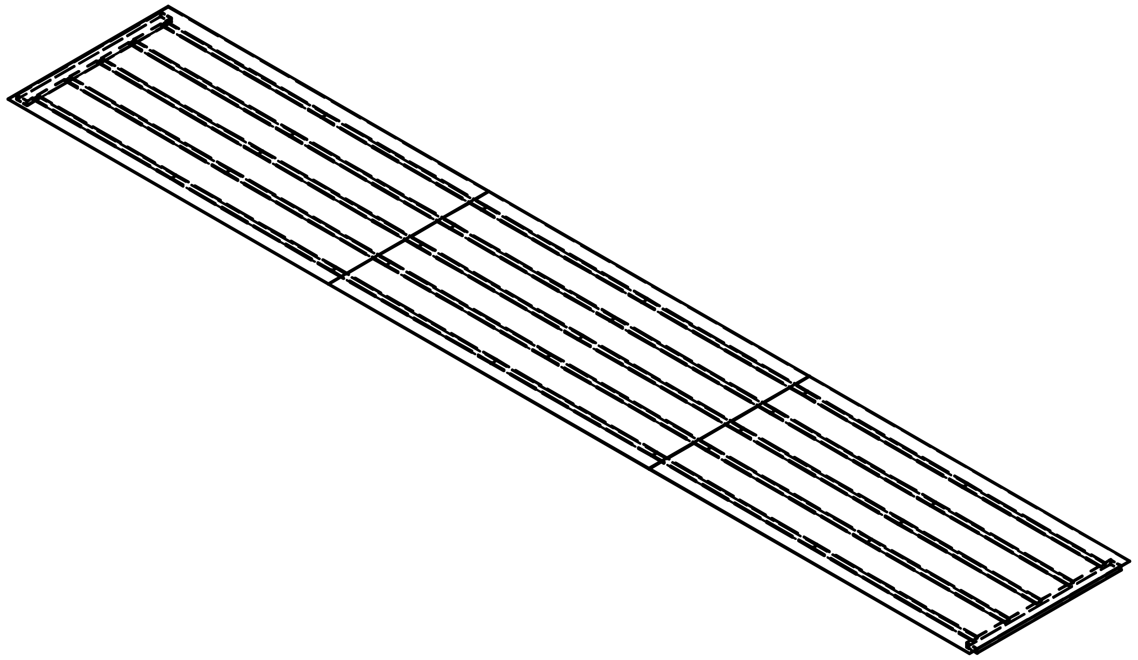




D-D (1 : 100)

E (1 : 15)





Dryer plate VS2.

All channels are made from bended plate
and welded on to the 10mm plate.

Disadvantage:
Lot of welding that have to be of a high quality due to the PED.
Time consuming due to the amounts of welding.

Drawing number

Title
Tørreplade A 3 stk

Project

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Weight
4566,4 kg

Finish

Scale
1 : 100

Material

Dimensions without tolerance:
Without decimal: ±0,3
1 decimal: ±0,1
2 decimal: ±0,01
3 decimal: Only CNC.

Not Specified chamfers: Max 0,5
Not specified radius of curvature: Max 0,5
Angle without decimal: ±3°
Angle with 1 decimal: ±1°

A3

Designed by
JJN

Checked by

Approved by

Date
25-06-2015

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Solution 2

A second solution is the welding of semi-cylindrical channels welded at the bottom of a 10 mm thick steel plate.

Figure 90 Sketch of the second drying plate solution

The advantage of this solution is the pressure resistance of (semi) cylindrical parts that would facilitates the approval of the design regarding the Pressure Equipment Directive.
The amount of high quality welding required is also problematic with this design. Another downside is the space taken by this solution: for the same exchange surface area, this design will result in a higher depth of the channels compare to the first design.

Solution 3

The last solution considered is a double layer drying plate. Two steel plates of 10 mm thickness are welded together with a space of 40 mm in between. A pipe containing hot water is placed between the drying plates as heating coil. The volume between the pipe and drying plates is filled with glycol for transferring the heat to the drying plates. Glycol is chosen for its high boiling point (190°C).

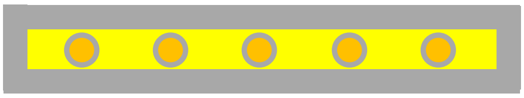
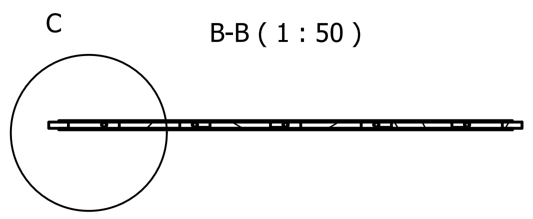
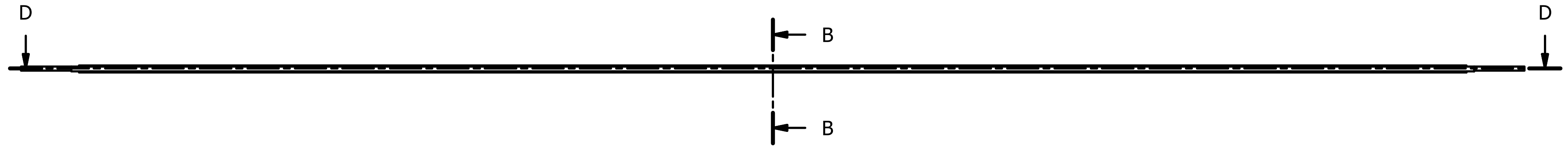


Figure 91 Sketch of the third drying plate solution

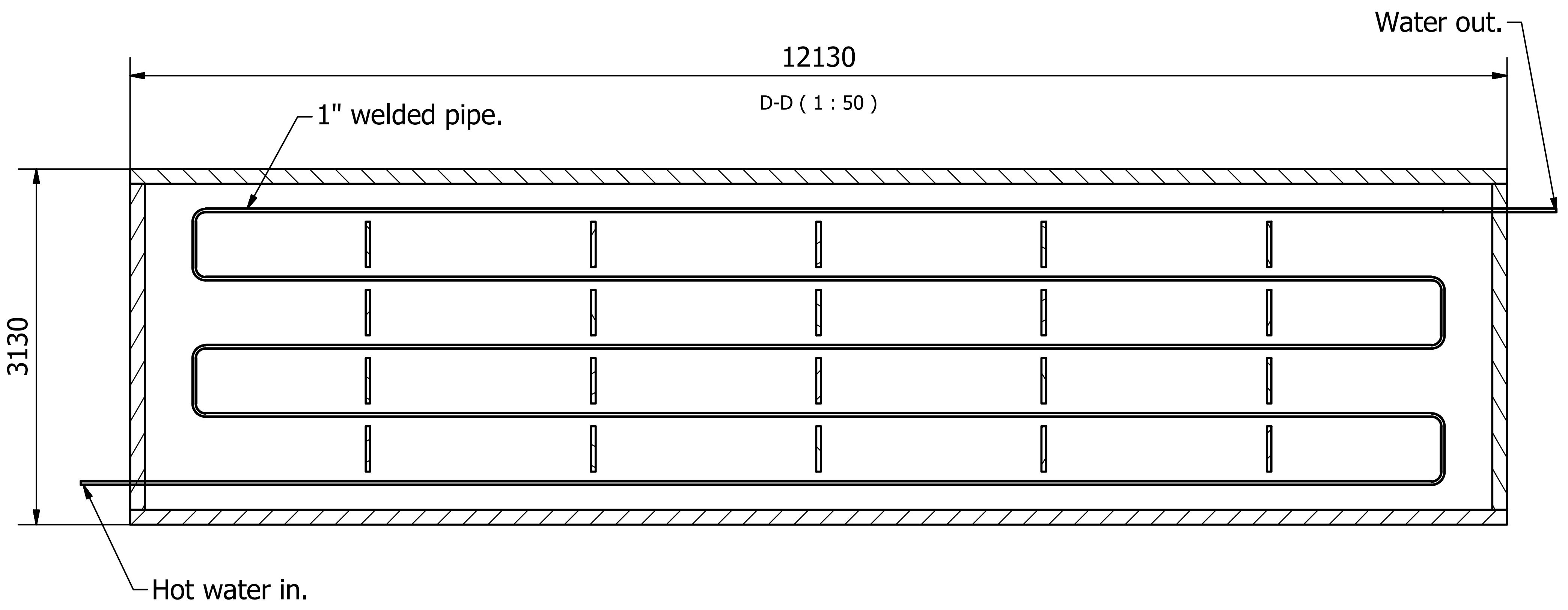
This construction has the advantage of reducing a lot the amount of welding that musts fulfil the Pressure Equipment Directive. Only the pipe has to withstand the pressure.
The heat transfer of this solution has to be estimated. It could be a show stopper if the glycol limits too much the amount of heat that can be transferred to the drying plate.

B-B (1 : 50)

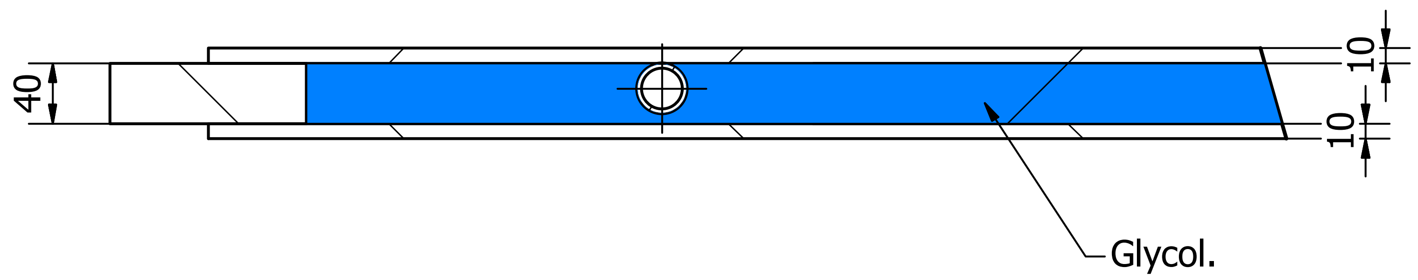




D-D (1 : 50)



C (1 : 5)



Dryer plate VS4.
Only the pipe inside has to be made according to PED.
Less welding to be done compared to previous dryer plates.
To be filled with glycol for transport of heat from pipes.
Glycol is chosen because of a boiling temp at 190 C°.
Glycol is preferred instead of oil because of the risk og leaks in the system.

Drawing number

Title
Tørreplade samlet

Project

Weight

Finish

Scale
1 : 50

Material

Dimensions without tolerance:

Designed by
JJN

Checked by

Approved by

Date
31-08-2015

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A3

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6.4. Force test setup

In order to have reliable data for the sizing of the mechanical driving system, a setup for test of force when moving sewage sludge will be built. The setup consists of a set of scrappers where different parameters can be changed and tested, and where the force necessary for moving the mechanism can be measured.

The setup consists of a chamber in which two scrappers are pulled by a hydraulic piston. The design is shown on the drawing next page.

Parameters

The parameters that can be changed and tested are:

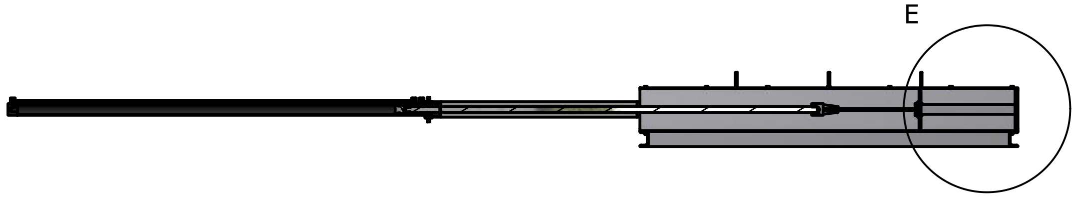
- Height of the scrappers, changing the thickness of the sewage sludge layer
- Distance between the two scrappers
- Moisture content of the sewage sludge
- Velocity of the scrappers

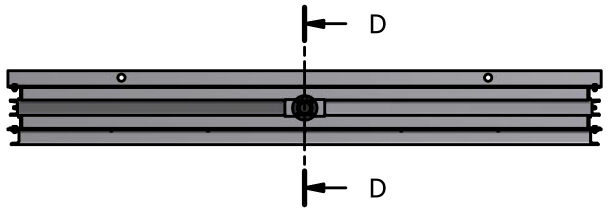
Measurements

- Force pulled by the hydraulic piston (the hydraulic pressure in the piston chamber is measured and the force is calculated by dividing by the area of the piston)
- Bending of the scrappers

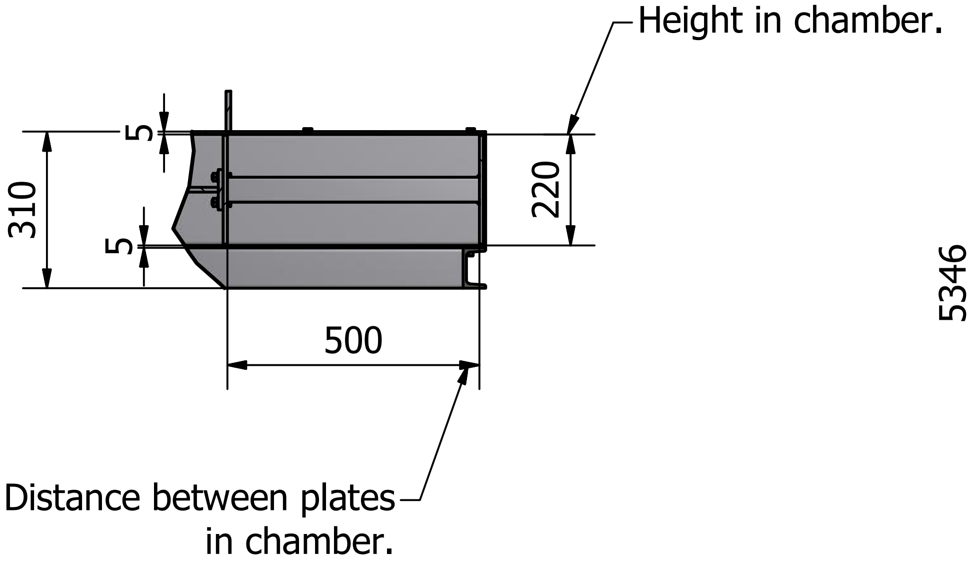
These experiments will give an accurate idea of the force to be expected for the final construction. Evolution of force and bending will be analysed in function of the parameters values and the operating parameters and sizing of the system will be based on the results.

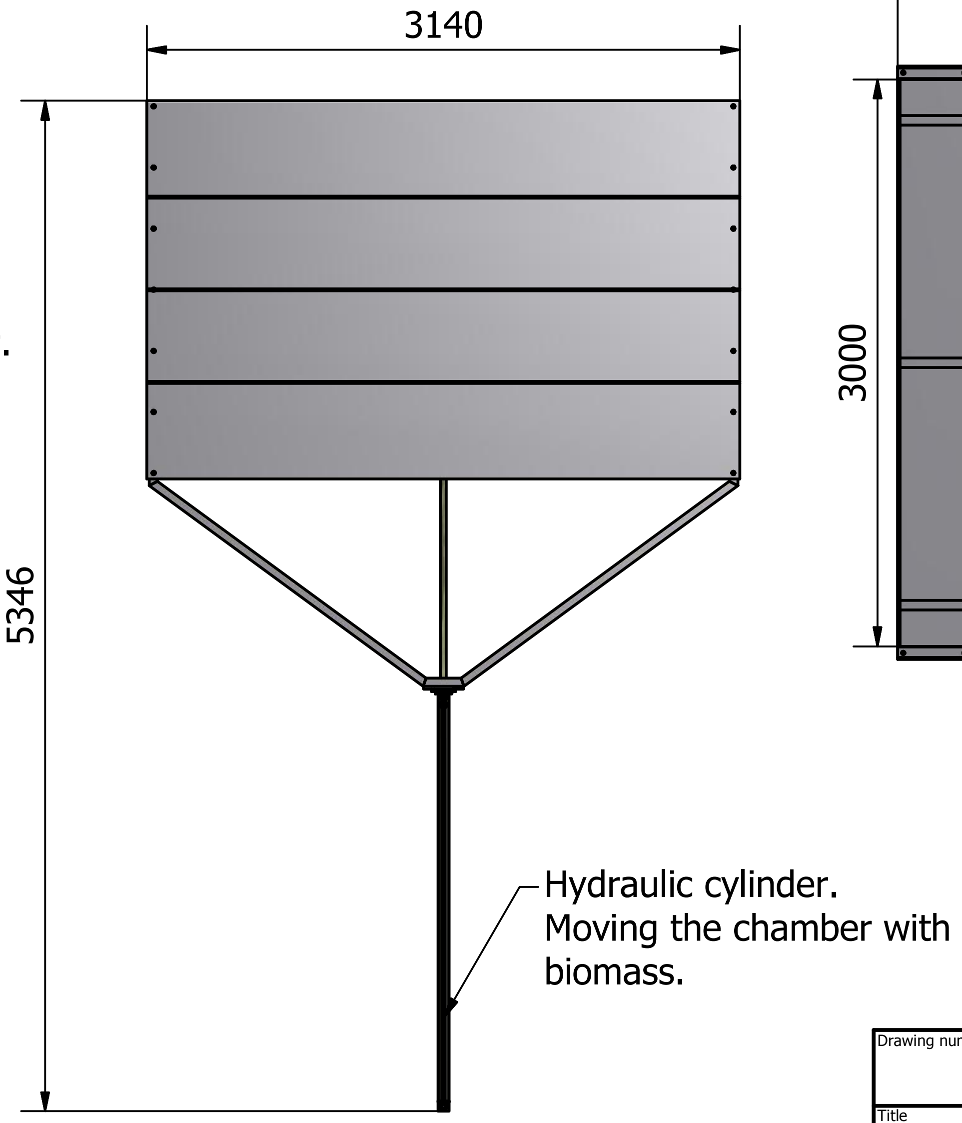
D-D (1 : 40)



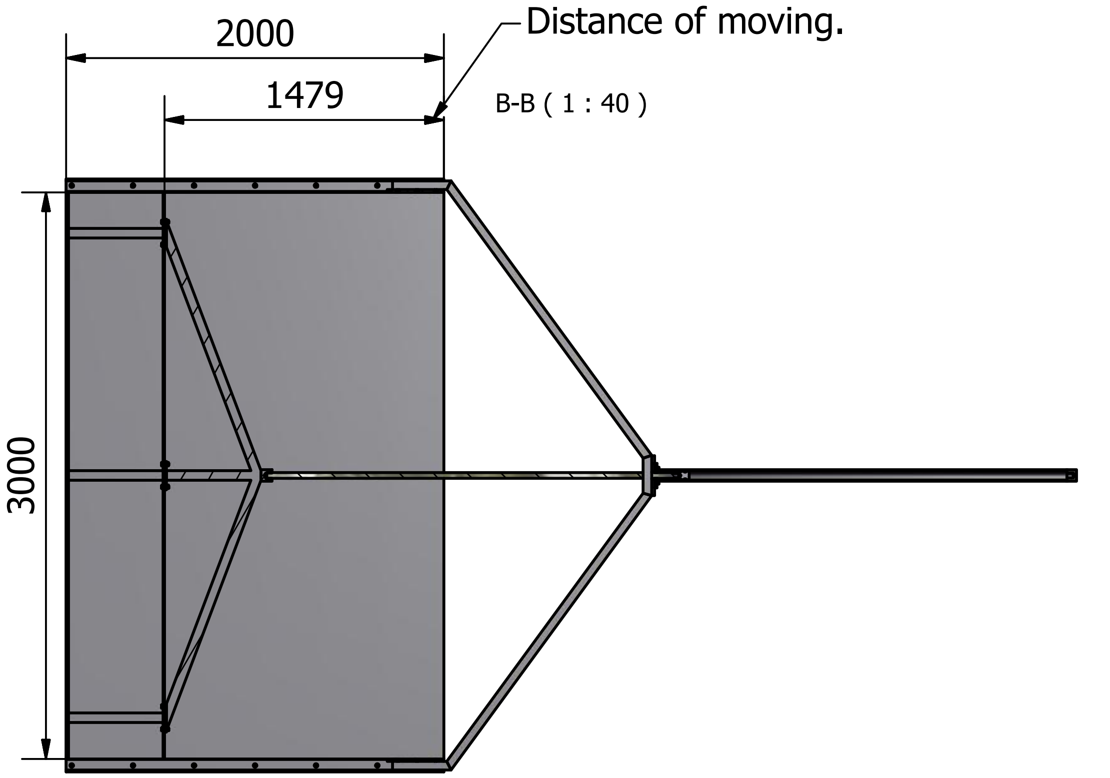


E (1 : 15)

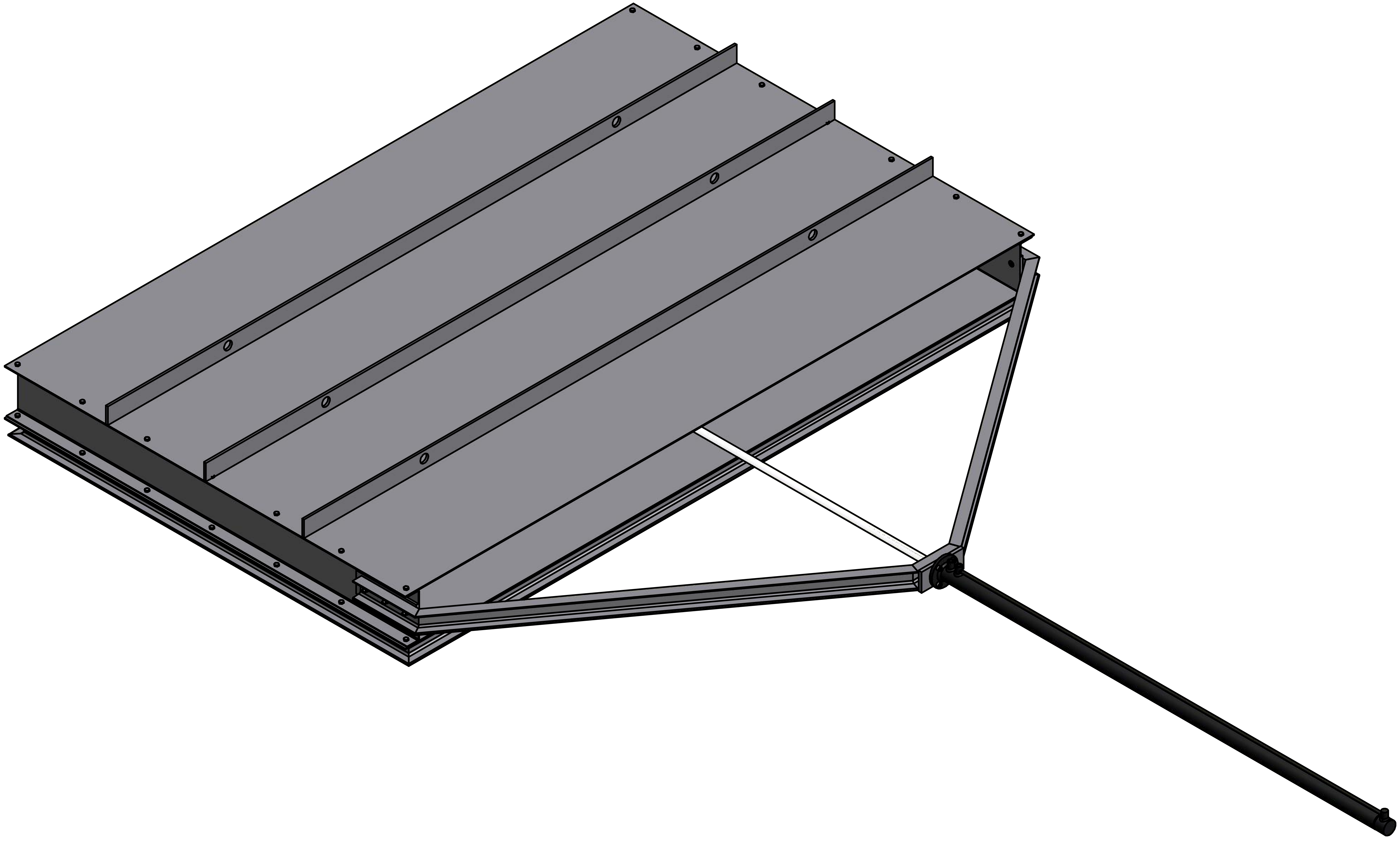




B-B (1 : 40)



Drawing number					**TK Energy Aps.** Junkers Industripark Værftvej 8 4600 DK-Køge Phone: +45 4618 9000 Fax +45 4618 9018 E-mail: tk@tke.dk
Title **Testopstilling samlet**			Project		
Weight 881,0 kg	Finish		Scale 1 : 40	Material	
Designed by JJN	Checked by	Approved by	Date 02-09-2015	**Dimensions without tolerance:** Without decimal: ±0,3 1 decimal: ±0,1 2 decimal: ±0,01 3 decimal: Only CNC. Not Specified chamfers: Max 0,5 Not specified radius of curvature: Max 0,5 Angle without decimal: ±3° Angle with 1 decimal: ±1°	A3 1 /2



Drawing number

Title
Testopstilling samlet

Project

Weight
881,0 kg

Finish

Scale
0,03 : 1

Material

Designed by
JJN

Checked by

Approved by

Date
02-09-2015

Dimensions without tolerance:
Without decimal: ±0,3
1 decimal: ±0,1
2 decimal: ±0,01
3 decimal: Only CNC.

Not Specified chamfers: Max 0,5
Not specified radius of curvature: Max 0,5
Angle without decimal: ±3°
Angle with 1 decimal: ±1°

A3

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7. Conclusion and perspectives

The expertise of TK Energy regarding preparation and dosing of fuel for entrained flow gasification has really been strengthened by the FLOWGAS project and its very good results. Three main elements should be highlighted:

- TK Energy is able to dose different biomass powders at atmospheric and pressurised conditions. The accuracy and stability of the flow has been characterized through experimental tests up to 40 bars.
- The complete company has been upgraded for the production of the CEA pressurised facility and has since the possibility to produce more easily pressure equipment. The first results and demonstrations of the FLOWGAS project have been a decisive factor in the sale of this facility.

The basic design and engineering of the sewage sludge dryer has been conducted. This pre-study has given a good idea of how the dryer should be constructed and the continuation of its development is being done through the 10 MW Pressurised Entrained Flow Gasification project (14-2 / 64014-0538) supported as well by the Danish Energy Agency.

Aside these three main results, TK Energy has demonstrated a complete supply line of fuel material from initial storage to injection at atmospheric conditions. Combined with the pressurized feeder technology of TK Energy and the promising results of pressurized dosing experiments, TK Energy has got the confidence for building a complete pressurized gasification facility.

Regarding the preparation of the fuel, the development of the dryer coupled with the downsizing technology developed through the NOWEAR project (EUDP 14-1 / 64014-0136) will be the solution for providing dry and downsized fuel material.

Based on these elements, TK Energy is applying for the construction of a 16 MW Pressurized Entrained Flow Gasification plant in Køge. The plant would include an up-scaled and pressurized version of the technology developed through the FLOWGAS project.

Table of figures

Annexes

Annex 1 Characterization of the sewage sludge

In order to know the characteristics of the sewage sludge before to gasify it, 5 samples have been taken from different places of the sludge storage. The moisture content and the ash content have been evaluated.

Moisture content

To determine the moisture content, a moisture determination balance has been used (OHAUS MB200). This device permits to weigh a sample in continuous during the drying.

The mass of the sample has been chosen of 5 grams +/- 0.1 grams.

The temperature variation of the OHAUS MB200 is +/- 1 °C. The drying temperature has been set at 103 °C to ensure the evaporation of water while avoiding reactions in the sewage sludge which can start with higher temperatures.

The drying time has been determined by doing a test during 2 hours with monitoring of the moisture measurement every 10 minutes. It has been concluded that 90 minutes are enough to dry a sample of 5 grams because no weight variation was detected after 90 minutes.

Results

Date	Sample	Sample weight (g)	Temperature (°C) +/-1°C	Time (min)	Moisture content
16-10-2013	1-1	5,00	103	90	25,9%
17-10-2013	1-2	5,00	103	90	26,7%
17-10-2013	1-3	5,01	103	90	26,9%
17-10-2013	2-1	5,03	103	90	24,5%
17-10-2013	2-2	5,05	103	90	25,1%
18-10-2013	3-1	5,00	103	90	42,3%
18-10-2013	4-1	4,93	103	90	50,7%
18-10-2013	5-1	5,09	103	90	26,8%

The first three tests (1-1, 1-2 and 1-3) have been made to evaluate the variation of the moisture measurement. We can see a variation of 1% of the moisture content for the same sample. This variation can be due to the device precision and also to the sludge which is not homogeneous. This variation is totally acceptable in the sense that the goal of these tests is just to estimate the moisture content.

If we look at the 5 samples, we can see that the moisture content is between 25% and 50%. The sewage sludge is not homogeneous and the moisture content changes in function of where we take the sample.

Ash content

The ash content has been determined thanks to an oven HERAEUS MR170 and a balance OHAUS E300J (readability 0.01 gram).

The mass of sample used was between 2.5 and 4 grams. The sewage sludge used has been previously dried as explained in the first part “Moisture content”.

The temperature of the oven was set at 575 °C. The temperature variation of the oven is about +/- 20 °C.

Each sample has been heated during 4 hours. By weighing the sample before and after, we could determine the ash content.

Results

Date	Sample	Time	Oven setting	Temperature (°C) +/- 20°C	Tare	Weight 1	Weight 2	Ash Content
17-10-2013	1	4h	6,2	570	114,25	4,00	1,04	26,0%
17-10-2013	2	4h	6,2	570	114,29	4,00	1,00	25,0%
18-10-2013	3	4h	6,2	570	144,24	2,99	0,77	25,8%
21-10-2013	4	4h	6,2	570	114,28	2,57	0,67	26,1%
21-10-2013	5	4h	6,2	570	144,24	3,99	1,03	25,8%

We can see on these 5 experiments that the ash content is about 26% and the ash content variation is very low (+/-0.2%).

It means that if we can dry the sewage sludge homogeneously then the characteristics of the sewage sludge (ash and moisture content) will be known with accuracy and will not influence a lot the process of gasification.

Annex 2: Evaluation of the bridge breaker torque

The dosing bin is equipped by a bridge breaker in order to avoid any variation of the dosing flow by moving the material above the dosing screw and thereby ensure a full filling of this screw.

The torque needed for the rotation of the bridge breaker is very difficult to calculate. A lot of properties and parameters have to be taken into account for this calculation.

A first gearmotor has been mounted to drive the bridge breaker of the dosing bin:

- Power = 3 kW
- Motor speed = 1475 rpm
- Gear ratio i = 61.6
- Speed rotation at 50 Hz = 23.9 rpm
- Torque at 50 Hz = 1200 Nm

This gearmotor is enough powerful for a use with CEA powder but does not have enough torque to work with torrefied powder.

An evaluation of the torque needed has been done by experimentation (Figure 1. & Figure 2.) in order to select a gearmotor suitable for this application.

Figure 1. Picture of the experiment

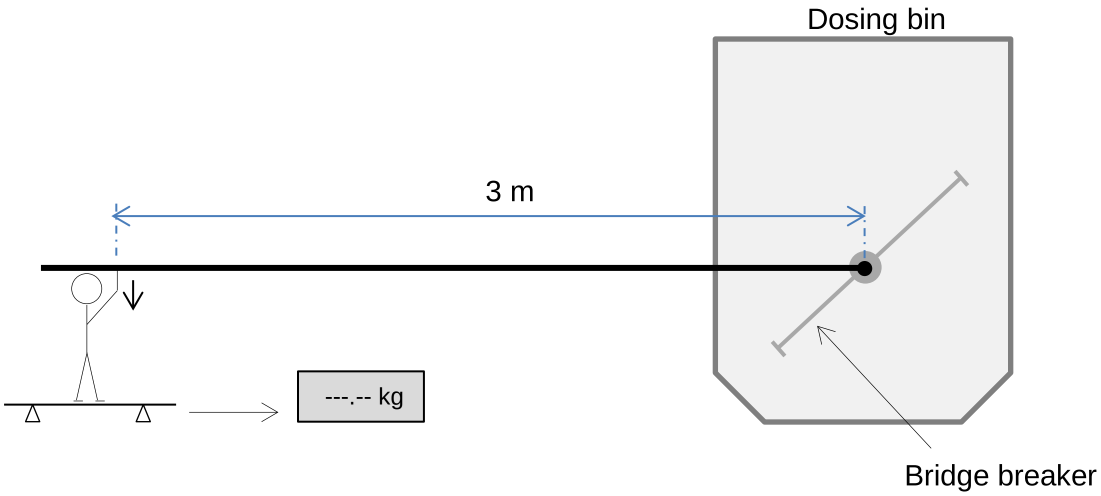

Figure 2. Sketch of the torque measurement method

Torque applied by the pipe

$lenght\ of\ the\ pipe = 3.4\ m$

$mass\ of\ the\ pipe = 13.6\ kg$

$torque\ applied\ by\ the\ pipe\ \tau_1 = m * g * \frac{l}{2} = 13.6 * 9.8 * \frac{3.4}{2} = 227\ Nm$

Torque test with CEA powder

The properties of the CEA powder are close to the properties of wheat flour which will probably be used as starting fuel for the gasification.

The mass applied on the pipe to move the bridge breaker with CEA powder is about 22 kg, equivalent to:

$$\tau_2 = m * g * l = 22 * 9.8 * 3 = 647\ Nm$$

The total torque is therefore:

$$\boxed{\tau = \tau_1 + \tau_2 = 874\ Nm}$$

Torque test with torrefied wood powder

The properties of torrefied wood powder are close to the properties of the sewage sludge that will be used as fuel for the gasification.

The bridge breaker rotated with a 95 kg mass pulling at the end of the pipe, equivalent to:

$$\tau_3 = m * g * l = 95 * 9.8 * 3.4 = 3165\ Nm$$

The total torque is therefore:

$$\boxed{\tau = \tau_1 + \tau_3 = 3392\ Nm}$$

Conclusion

Thanks to this study of the torque requested to ensure the rotation of the bridge breaker, we will be able to dimension the gearmotor that we need.

The rotating speed of the bridge breaker gearmotor is known and is function of the mass flow of material to feed to the gasifier.

With the rotating speed and the torque, we know which power the motor must have to drive the bridge breaker.