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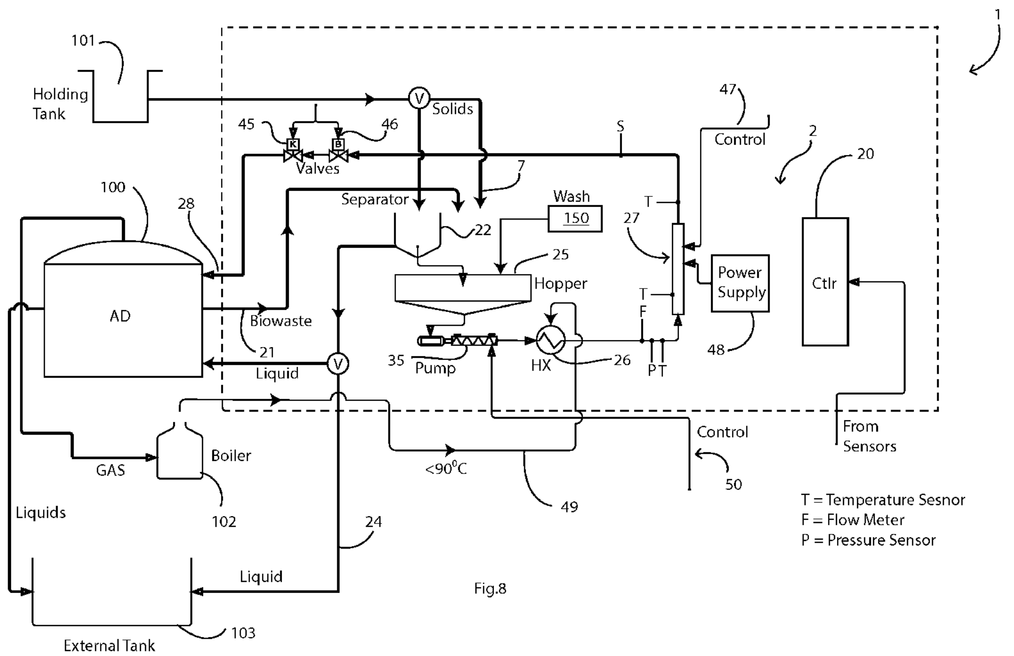

Fig.8

(57) Abstract: A biomass treatment system (1) comprises a separator (22), a microwave reactor (27), a pump (35) to deliver solids output from the separator to the microwave reactor. There is a reactor outlet (28) with a valve (45, 46) for delivering microwave-treated digestate to an external AD (100). A controller (20) controls the separator to provide feedstock with a desired solids content to the microwave reactor (27) and controls the microwave reactor for desired treatment of the feedstock. The system (1) is modular with couplers for coupling to an AD system (100-103) to provide a combined system, in which the microwave reactor (27) provides treated feedstock for an AD.

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"Improvements Relating to Anaerobic Digester Systems and Methods"

INTRODUCTION

Field of the Invention

The invention relates to anaerobic digestion ("AD") systems and to methods of treating biomass with AD.

Anaerobic digestion is a fermentation-like process by which microorganisms break down biodegradable material in the absence of oxygen, with bacterial hydrolysis of biomass feedstock. It is typically used to treat biodegradable waste and sewage sludge, to provide useful by-products including "biogas" and to reduce the emission of landfill gas into the atmosphere. Due to biogas production AD is widely used as a source of renewable energy, as the biogas can be used directly as fuel, in combined heat and power gas engines or upgraded to natural gas-quality biomethane. The nutrient-rich digestate also produced can be used as fertilizer. The field of anaerobic digestion optimisation and improvement is one that has gained significant interest for technology providers and end users. This is due to the increased need to optimise and improve the general performance of AD, measurable for the main part by increased biogas output, lower processing time and improved breakdown of recalcitrant feedstock materials. Improvements in these areas elevate the economic viability of what is typically a capital-intensive process.

Pre-treatment of waste materials thermally by microwave irradiation is one method of enhancing biogas production in anaerobic digesters. Microwave irradiation changes the secondary and tertiary structure of proteins of microorganisms, and is an efficient method for disintegrating sludge particles due to fast cell lysis.

WO2016/116745 (University of York) describes a method of transformation of cellulosic material in which there is microwave assisted hydrothermal treatment. EP1978086 (Stirl) describes production of biogas from biomass in which there is microwave treatment.

So far, successful applications of microwave technology have been primarily in the synthesis of high value compounds such as pharmaceuticals, sterilization of hazards, and extraction of higher value natural products.

The invention is directed towards more effective AD treatment of biomass feedstocks, especially with use of microwave irritation.

In this specification the term “biomass” is intended to mean any material which is amenable to anaerobic digestion, sometimes referred to alternatively as “bio-waste”. The term “AD” is an abbreviation of “anaerobic digester” or “anaerobic digestion”, according to the context.

<u>Summary of the Invention</u>

We describe a biomass treatment system comprising a separator, a microwave reactor, a pump arranged to deliver solids output from the separator to the microwave reactor, and a reactor outlet with a valve, arranged to delivery outlet feedstock to an anaerobic digester, and a controller. Preferably, the controller is configured to control the separator to provide feedstock with a desired solids content to the microwave reactor and to control the microwave reactor for desired treatment of said feedstock for subsequent downstream anaerobic digestion. Preferably, the system comprises a feedstock direct intake separate from the separator, and interfaces (7, 21) arranged to receive feedstock into the direct intake or into the separator, both being linked with the microwave reactor. Preferably, there are couplers for coupling the treatment system to an external anaerobic digester to provide a combined system.

Other aspects of the system are set out in the accompanying claims 2 to 29, incorporated herein.

We also describe a method of operation of a system of any example, the method comprising:

delivering a biomass feedstock to the separator,

the separator separating the feedstock into a solids fraction and a solids fraction,

feeding the liquid fraction to an outlet,

feeding the solids fraction to the heat exchanger,

the heat exchanger pre-heating the feedstock,

pumping the pre-heated feedstock to the microwave reactor,

the microwave reactor treating the feedstock by elevating temperature of the feedstock, and

delivering the treated feedstock to an anaerobic digestion system.

Other aspects of the method are set out in claims 31 to 37, incorporated herein.

Additional Statements

We describe a biomass treatment system comprising a separator, a microwave reactor, a pump to deliver solids output from the separator, or other source, to the microwave reactor, and a reactor outlet with a valve, and a controller to control the separator to provide feedstock with a desired solids content to the microwave reactor and to control the microwave reactor for desired treatment of said feedstock.

The system may be modular, with couplers for coupling to an AD system to provide a combined system, in which the microwave reactor provides treated feedstock for an AD.

The separator may be linked with a coupler to receive partially digested feedstock from an AD.

The separator may be linked with a coupler to deliver liquid portion to an external tank of an AD system.

The system may comprise a direct feedstock intake separate from the separator, and couplers or other interfaces arranged to receive feedstock into the direct intake or into the separator, both being linked with the microwave reactor.

The separator may be arranged to deliver a solids portion into said direct intake.

Preferably, the couplers are arranged to receive feedstock into either the separator or the direct intake which are either partially treated by an AD or not.

Preferably, the controller is programmed to operate in one or modes of operation which may be user-selected, said modes differing according to nature of feedstock and/or paths through the system. Preferably, a mode is for untreated biomass such as slurry directly to the direct intake and which is pumped to the microwave reactor. A mode may be for untreated biomass such as slurry fed to the separator. A mode may be for treated biomass fed directly to the direct intake and which is pumped to the microwave reactor. Preferably, a mode is for treated biomass fed to the separator.

The controller may be programmed to process for a selected mode according to a desired volume of feedstock received. Preferably, the controller is programmed to automatically start a wash cycle for at least some components and pipes upon completion of a mode for a set volume.

Preferably, the system comprises a heat exchanger in a path from the separator to the reactor. Preferably, the system comprises a heat exchanger in a path from a direct inlet to the microwave reactor.

The heat exchanger may be linked to both the separator and to the direct inlet. Preferably, the heat exchanger is directly linked to the direct inlet and is linked via the direct inlet to the separator. The direct inlet may comprise a hopper.

Preferably, the heat exchanger comprises couplers for linking to a hot water supply such as that from a boiler fed by biogas. Preferably, the heat exchanger and the controller are arranged to increase temperature of feedstock to a value in the range of 30°C to 80°C.

Preferably, the system comprises valves downstream of the reactor and being operatively linked with the controller to control residency time and/or temperature within the reactor.

Preferably, the system the valves comprise a knife valve and or ball valve. Preferably, the controller is programmed to operate only one of said valves at any one time.

Preferably, the system comprises a housing arranged to be mounted on a vehicle and to be linked to an external system as a modular unit. The housing may be of box rectangular shape.

We also describe a combined treatment system comprising a treatment system of any embodiment and a coupled anaerobic digester system arranged to supply digestate to the separator and to receive microwave-treated digestate from the microwave reactor.

DETAILED DESCRIPTION OF THE INVENTION

Brief Description of the Drawings

The invention will be more clearly understood from the following description of some embodiments thereof, given by way of example only with reference to the accompanying drawings in which:-

Fig. 1 is a perspective view of a biomass microwave treatment system for hooking up with an anaerobic digester (AD) system, and Fig. 2 is a similar view with the housing removed;

Fig. 3 is an external side view of the system;

Fig. 4 is an internal plan view of the system, in the direction A-A of Fig. 3;

Fig. 5 is an internal side view in the direction of the arrows B-B of Fig. 4;

Fig. 6 is an internal side view in the direction of the arrows D-D of Fig. 4;

Fig. 7 is an internal end view in the direction of the arrows C-C of Fig. 5;

Fig. 8 is a process flow diagram showing layout of the components of the system in process terms and how they hook up with an external AD system to form a combined microwave and AD treatment system; and

Figs. 9 to 15 are plots showing results from use of the system in various examples.

Description of the Embodiments

Referring to Figs. 1 to 7, a biomass microwave treatment system 1 is modular, being configured for transport on a vehicle trailer to the site and hooked up with an external AD plant, or it can be operated as a complete treatment plant on its own. A series of containers may be stacked together, given the modular nature of the system.

The treatment system 1 comprises a rectangular box housing 2 configured to fit on a flatbed trailer for haulage to site. The housing 2 has an end door 3, a side roller door 4, and a side hinged door 5. There is an access gangway 6 at a central location for personnel access. This is alongside a hopper feed manhole 7, in turn alongside a screen cover 8. A microwave plant outlet coupler 28 is mounted on the roof of the housing alongside the gangway 6.

Referring also to Figs. 2 to 7, internally, the system 1 comprises a computer controller 20 which is linked with all of the automated components for control of the system 1 in an integrated manner.

There is a biomass feedstock inlet 21 to a separator 22, which has a liquid outlet coupler for delivery from the system 1, and an internal solids outlet into a hopper 25. The access opening 7 is also provided for delivering additional solids into the hopper 25 as is required. A pump 35 delivers hopper 25 outlet material through a tubular heat exchanger 26 to a microwave treatment reactor 27. This is linked with the outlet 28, through the roof of the housing 2, as is visible in Fig. 1. In this example, an hydraulic pack 36 is mounted close to the microwave plant 27.

The microwave reactor 27 has a vertical orientation with a tube conveying the feedstock pumped by the pump 35, and a surrounding air jacket. The microwave radiation is provided by a generator and magnetron to the side which has a waveguide directing the radiation transversely across the tube, which is transparent to such radiation. The magnetron generates microwaves with a frequency in the range from 896 to 915 MHz. The corresponding wavelengths that provide radiation in the reactor 27 are typically in the range of 43 to 46 cm.

The separator 22 is a vibratory mesh which is oriented with an acute angle of less than 45° to vertical and is curved downwardly and outwardly with an enlarging angle to vertical. The liquid component falls through the mesh apertures to be directed to the AD 100 or to the tank 103 according to valve operation by the controller 20. The solids portion, for example fibrous material from slurry, slides downwardly over the mesh and is directed into the hopper 25.

The heat exchanger 26 is of the shell and tube type, with a number of parallel tubes of internal diameter of about 20 cm and a length of about 6m. The tubes are surrounded by water in a jacket, and the water preferably has a temperature in the range of 50°C to 90°C. The heat exchanger 26 also includes scrapers for the tubes, each scraper being on a piston which is pushed into and retracted from the tube. This ensures that feedstock material does not adhere to the tube internal surfaces.

Referring to Fig. 8 this diagram shows the flows within the system 1 and also the manner in which it hooks up with external equipment when desired for combined microwave and AD treatment. This diagram shows additionally a knife valve 45 and a ball valve 46 in the microwave outlet 28, which hooks up to an anaerobic digester 100. Any other suitable valves could be used instead, especially those falling under the category of a pressure valve. The valves 45 and 46 are operated to maintain a desired pressure in the system, especially a desired residency time and temperature in the microwave rector 27, as they are downstream of the reactor 27. Hence the controller 20 operates the pump 35 and the valves 45 and 46 in tandem in order to optimize pressure and dwell times and flow rates in the reactor 27.

A control line 47 to the microwave reactor 27 is from the controller 20, in turn linked with the sensors. In particular, the controller 20 can control microwave power and pump speed 35 according to temperature required in the reactor 27, typically in a range of 30°C to 150°C. Microwave energy is delivered from a power supply 48. Temperature sensors in the reactor 27 and its outlet line provide feedback to the controller 20 which in turn controls the valves 45 and 46 and also the feed pump 35 and the microwave energy power supply 48 to maintain a desired pressure and temperature within the reactor 27 and indeed in the whole system components which convey feedstock upstream of the reactor 27. The typical pressure range is 1 to 10 bar. A related parameter is residency time in the reactor 27.

Fig. 8 also shows a coupler 49 from an external boiler or hot water source 102 which may be powered by gas from the AD 100. Hot water of 50°C to 90°C is conveyed through the coupler 49 to the heat exchanger 26, which uses this energy to bring temperature of the feedstock up to a value in the range of 30°C to 80°C in some examples, or in other examples to a value in the range of 30°C to 90°C. This pre-heating provides for very effective use of microwave power, and overall energy efficiency due to the fact that it uses energy derived from AD gas. Moreover, this hot water supply may be used for washing cycles within the system 1. A control line 50 to the feed pump 35 allows the controller 20 to inhibit operation of this pump if the hopper 25 level is excessively high or low, or if pressure, heat or power parameters exceed user-set levels.

Fig. 8 also illustrates a wash system 150, which directs wash water into the hopper with sufficient pressure to wash through the reactor 27 and the intervening components. This is done between batches.

In general, the controller 20 receives via a user interface an indication of the amount of feedstock to be processed and/or the desired temperature in the microwave reactor, and the controller automatically checks level in the hopper 25, and sets pumping to match the maximum separator incoming flow rate. Fig. 8 shows some of the main pressure, flow, and temperature sensors of the system, but it is not limited to these locations. Advantageously, the hopper 25 is arranged to receive either or both of separated material and other material directly deposited into the hopper 25. Hence the system 1 can treat material partially treated by an AD before a route through the microwave reactor 27 and onwards to the AD 100 again. Both can be used in combination at the same time, i.e. separated material and other material deposited into the hopper 25. The feedstock may be supplied from a holding tank 101 or other source to the separator 22 or directly to the hopper 25 according to valve control by the controller 20. Also, in some modes of operation, some or all of the feedstock may be delivered on a line 21 from the AD 100, in which case the feedstock is of a type for which a second pass through the microwave reactor 27 is desirable. The liquid component from the separator 22 may be directed to the AD 100 or to the external tank 103, again by appropriate valve control.

Advantageously, the system can hook up with external equipment to form a desired combined system in a versatile manner. The main interfaces are as follows, some or all of which can be used for any particular processing requirement.

(a) Feedstock hatch 7, especially useful for receiving un-processed material. Optionally the feedstock can bypass the hopper 25 and be fed directly to the heat exchanger 26 in other examples.

(b) Coupler 21 for receiving treated feedstock from the AD 100 or another unprocessed biomass 101. In another example there is a permanent conduit for delivery of such an intake directly to the hopper 25, or there may be a diversion valve arrangement for delivery to a selected one of the separator 22 and the hopper 25, or indeed directly to the HX 26. In many cases it is especially advantageous that the intake is separated by the separator 22 to provide downstream feedstock within the system to an exact requirement. Separation also creates a concentration of solid materials which can be more advantageous for microwave treatment.

(c) Coupler 49 for hot water from an external boiler or other source. This allows use of any suitable hot water source, but is particularly advantageous for using water derived from AD gas product.

(d) Liquid outlet coupler 24, which can be used to provide a desired consistency of liquid to an external plant such as the tank 103. This is provided without need to consume energy in the microwave reactor 27.

(e) Coupler 28 for delivering treated feedstock to external equipment such as the AD 100 as shown in Fig. 8. This can be delivered into an AD such as the AD 100 at a stage where it can be optimally further processed to provide the desired products. It is very advantageous that the coupler 28 includes the arrangement of valves 45 and 46 to assist delivery of treated feedstock, but to also control parameters of the microwave reactor 27 as described above.

As illustrated in Fig. 8 the external AD components may include an anaerobic digester 100, a holding tank 101, a biogas boiler 102, and a liquid tank 103. As described below the controller is programmed to process for a selected mode according to a desired volume of feedstock received. Preferably, the controller is also programmed to automatically start a wash cycle for at least some components and pipes upon completion of a mode for a set volume. The modes are selected to achieve desired targets such as a treated feedstock volume or mass or a desired temperature achieved in the microwave reactor i.e. the pump will adjust speed based on temperature achieved.

The HX 26 upstream of the reactor is preferably arranged to receive from any intake, either directly from the hopper 25, directly from the separator 33, or indeed directly from an external source. It is envisaged however that in use it is preferably to receive material from the separator and the hopper as these components allow optimum handling especially for desired solids content. It is particularly advantageous that the HX 26 is linked to a hot water supply such as that from the boiler 102 fed by biogas. The HX 26 can efficiently increase temperature of feedstock to a temperature in the range of 30°C to 80°C.

As described above, the HX 26 has an internal surface cleaning feature to avoid fouling. As biomass heats up it may foul the pipework and eventually lead to a build-up of unwanted material. Using a scraping action the walls of the tube are gently cleaned.

The microwave system 1 has in one example six user-selectable available modes of treatment processing, as follows:

1) Biomass directly from the holding tank 101 via the inlet 7, and bypassing the separator 22.
2) Biomass from the holding tank 101 via the interface 21 that has been separated by separator 22. This uses an interface not shown in Fig. 8, from the tank 101 into the coupler 21.
3) Digested material directly from the AD 100, via a coupler linking the AD 100 to the hopper 25.
4) Digested material directly from the AD 100 that is separated by the separator 22, received via the coupler 21. The purpose of the separation is to increase the solid fraction that will be used in the microwave reactor 27.
5) Biomass from any other source received via the hatch opening 7 to the hopper 25.
6) Biomass from any other source received directly via the inlet to heat exchanger 26.

In Modes 1 and 3 the biomass is pumped directly into the feed hopper 25 and all is processed through the microwave reactor 27 and then pumped into the AD 100 through the coupler 28. Both modes process a certain proportion of the daily AD intake. In a variation this mode may include cooling by an additional HX. If so, it is preferable that the temperature be reduced to 30°C to 60°C in order to reduce the temperature of the treated material to that of the biomass already residing in the anaerobic digester. The heat created in this additional HX could be utilised to pre heat untreated biomass going directly to the anaerobic digester.

In Modes 2 and 4 a separation technique is used to separate by the separator 22 the material into liquid and fibre fractions. The fibre fraction is always fed into the microwave reactor 27. In Mode 2 the liquid fraction from the separator 22 is pumped to the AD system tank 103 via the coupler 24, or it could be directly to the AD 100. In this case the separator 22 is of vibrating screen type, but it may for example alternatively be a screw press, belt press, or rotary drum. In Mode 4 the liquid fraction is pumped to the storage tank 103, or alternatively directly to the AD 100. In Mode 5 another suitable biomass can be entered into the collection hopper 25 for processing in an individual batch or as part of batch processed under modes 1-4.

A mode of operation is selected on the control panel of the controller 20 and a target volume (cubic meter) amount of biomass is entered. Other key parameters may be selected, such as a desired temperature based on the type of feedstock. Each mode can also have pre-set temperatures or amounts of material entered. Setting a volume amount allows the user to test different processing volumes and calibrate the optimum amount, which can then be pre-set.

A three-way valve, not shown, allows a feed to be directed either into the separator 22 or directly into the microwave hopper 25 depending on mode selected. Un-separated material is pumped to the hopper 25. This allows better mixing with any other material added to the hopper. The controller 20 is configured by programming so that only one mode will operate at any one time. The separator 22 has two output streams, the fibre (thickened) fraction goes directly to the hopper 25, while the liquid fraction is pumped to either i) the anaerobic digester 100, or ii) to the storage tank 103 depending on the mode.

In Mode 2 the liquid phase may be pumped into the anaerobic digestion tank 100 because the material has not yet been digested, and pumping directly to the storage tank 103 may not advantageous. The controller 20 can be pre-set to direct to either tank as is desirable for the biomass being processed. In Mode 4 the liquid output from the separator 22 is pumped to the storage tank 103 and input flow to the separator 22 is measured by a flow meter so that the controller 20 can monitor flow against the volume of biomass selected when the mode is selected at the outset. The action of the separator 22 is controlled by the height of the material within the hopper 25 and the separator maximum incoming flow rate. When a target temperature is set in the controller 20, the controller 20 sets flow rate of the pump 35.

The separator 22 is fed by a variable speed pump the speed of which is varied according to three inputs: one based on the volume amount selected for the mode; another from the separator itself, including the separator max incoming flow rate, which prevents the separator from overloading its screen; and the third from a level sensor in the hopper 25 to prevent the hopper from overflowing. As noted above a target temperature results in the pump 35 being controlled accordingly.

In some examples, the separator 22 utilizes a wash sequence. This separator wash cycle is integrated with a water flushing cycle. The separator washer is turned on every time the system wash cycle is called and stopped when the system wash cycle finishes. An override for separator-only wash should also be available. The override cannot run when any other mode is in operation. The wash water is pumped to the storage tank 103. The length of the wash cycle is configurable in minutes and is not longer than the system wash cycle time.

A three-way valve is controlled depending on the requirements of the selected control mode (feed from other feedstock source/feed from AD). A separator/hopper feed pump is controlled based on the volume selected for the mode, the separator maximum incoming flow, and the level in the feed hopper. A separator/hopper divert valve is controlled depending on the requirements of the selected control mode (feed to separator 22 for Modes 2 or 4, or feed to hopper for Modes 1, 3 or 5). A flow sensor monitors, and the controller 20 records, the feed flow and controls the speed of the feed pump.

Valves are arranged to allow flow monitoring of all modes (i.e. using separator and not using separator) and flow meters are arranged to measure the volume of biomass processed for any one mode against the selected volume for that mode.

In one example liquid from Mode 2 (separated biomass) is pumped to the AD 100 and not to storage tank 103. A storage level sensor monitors for the controller the storage level in the tank 103. Upon high level detection, if the separator is running it shall be inhibited.

Material is fed from the hopper 25 into the pump 35 from the auger – this pump is kept full while the phase is in operation. Sensors measure flow, pressure and temperature in this section of the line (26), all of which are recorded and processed by the controller 20. In order to stop any excessive back pressure to the pump, two check valves are included. Other valves may be used to achieve such control. Depending on the feed water temperature at the interface 49, the material is heated up to an expected 30°C to 80°C by the heat-exchanger 26, and the material passes through the microwave reactor 27 while being constantly measured for flow, pressure and temperature. The valves 45 and 46 are used to control the pressure in the line and in the reactor 27. This line also includes a safety blow out valve, which protects the system.

<u>Control, More Detail</u>

The control of the microwave power from the supply 48 is governed by *inter alia* the sensed reactor temperature, the rate of change of pressure in the reactor and linked lines, the existence of power in the pump 35 (it may not be running but it is powered on) and the pressure recorded on pressure sensors in the reactor and in adjoining lines and the pre-selected residency time. The hopper 25 feeds the auger underneath it, the auger delivers the biomass to the pump 35 ensuring that this pump feed is full (i.e. pressure above atmospheric in the line), and that the pump fills the microwave pipework. This is helped by the check valve directly after the pump – this pumping is intermittent in nature. The pump 35 keeps the system full of material, passing this through the heat exchanger 26 which brings it up to a temperature of 30°C to 80°C for example.

With the biomass passing through the microwave rector 27 and the temperature increasing up to 150°C (set-points configured in SCADA), this will increase the pressure within the microwave reactor, the check valve will stop any biomass returning and creating excessive back pressure on the pump, the pressure valve/ball valves 45 and 46 are modulated (via SCADA) to either maintain a pre-set pressure on the line 28 to the AD tank 100 therefore allowing the flow of biomass into the AD tank or to hold the biomass within the microwave reactor 27 for a predefined time at the setpoint temperature. If a HX is included downstream of the reactor 27 this is controlled to achieve a desired lower temperature of pre-treated feedstock for the AD 100. The desired temperature will typically be 30°C to 60°C in order to reduce the temperature of the treated material to that of the bio-waste already residing in the anaerobic digester. The heat created in this additional HX could be utilised to pre heat untreated bio-waste going directly to the anaerobic digester. If pre-set pressure is exceeded (in the range of 4-8 Bar for example) or the pre-set hold time or pre-set temperature is exceeded the microwave power is reduced, pump speed may be increased and the pressure/ball valve 45, 46 will open to quickly release the biomass into the AD line 28.

While such control is effective for safety, for optimal pre-treatment of the feedstock the modulation of the valves 45 and 46 is in a steady state for the desired pressure and dwell time in the reactor. Once the pressure within the microwave reactor 27 has reduced, closing the back-pressure regulator, the pump will "top up" the microwave pipework and the cycle will repeat. When the hopper 25 is full, pumping of incoming bio-waste will be inhibited. When the hopper 25 is empty for longer than a certain number of minutes and the set number of m^3 of biomass has been processed (set-points in the SCADA system) the microwave mode should be stopped and the wash cycle start. Once the mode has finished processing fully (the controller 20 has monitored the number of m^3 of bio-waste and the selected mode has processed) a wash flush and separator wash is initiated, cleaning the microwave circuit of biomass.

Sampling

The system 1 has the option to switch to a sampling mode during operation any of the Modes 1 to 6. This would be invoked on the control panel during a standard mode of microwave operation. Samples are taken from the point marked S in Fig. 8, downstream of the reactor 27.

Once sampling mode is invoked, a valve is opened to the alternate biomass line and a valve is opened to the sampling line. The product then passes into a sampling holder. The user will switch off sampling mode when there is enough of a sample in the steel sampling container. The functionality to predetermine sample volume size or sampling time is preferred. Hot water from the boiler 102 or another source is fed through the heat-exchanger 26, which is controlled by a valve and the temperatures on the flow and return are measured along with the flow rate to measure the energy extracted from the water. The heat exchanger 26 valve can be operated when microwave feed is in progress and a flow meter records water in the line. Temperature sensors monitor, and the controller 20 records, the pre-heat exchanger water temperature and the post-heat exchanger water temperature, and the controller performs a calculation to determine the heat exchanged, and this is recorded on SCADA. Also, a flow sensor monitors the heat exchanger flow rate.

Once the microwave process is finished (pre-set number of m^3 processed and hopper has been empty for X number of minutes) a wash flush is initiated, cleaning the microwave circuit of biomass. The wash sequence includes two stages: (1) the flush water is fed directly from the cold-water supply into the auger using the pump 35 to pump the flushing water through the system, and (2) the flush water is fed to a booster wash pump flushing water through the system at a greater pressure. The heat exchanger 26 should remain operational to enable the flushing water to be heated for better cleaning performance. The flushing water is diverted into the storage tank 103 or another waste water tank. A manual initiate button for a wash sequence can be used providing the microwave is not in operation. Wash sequence shall be inhibited if a high level exists in the Storage Tank 103. In some examples, once the wash sequence finishes the water circuit valves should switch back to the AD heating.

In the Mode 4, digestate separated and microwaved digestate from the AD tank 100 is taken and processed through the separator 22 to reduce the liquid content, resulting in a solid fraction for processing.

Once the microwave process comes to an end, this line will require cleaning, which is the purpose of this flushing process. The microwave reactor 27 is switched off, the hopper is filled by the wash system 150 to a level with water which is pumped at the highest flow rate that the mono pump can achieve. After a period, the wash sequence shall enter a 2nd stage which will pump wash water through the microwave via the water booster pump. This water is discharged into the storage tank 103 (or another tank), by redirecting the appropriated valves. During this wash cycle the separator automated washer should also be invoked. It should not run longer than the system wash cycle.

Examples (Figs. 9 to 15), Tests Using the System 1

In general it has been found that the system is preferably operated with parameter values within one or more of the following ranges:

the separator provides a solids fraction with a solids content of the range of 8% to 30% dry matter,

the heat exchanger elevates temperature of the solids fraction to a value in the range of 30°C to 80°C,

the microwave reactor elevates the feedstock temperature to a value in the range of 30°C to 150°C,

the microwave reactor temperature ramp-up time duration is up to 20 seconds, and

the pressure in the microwave reactor is in the range of 0.5 Bar to 6 Bar.

Key

Inoculum = 600g of inoculum was added to 1L HDPE reactor bottles. Reactor heads with mixer paddles were added to induce continuous mixing. Samples were placed in a water bath at 37°C for 14 days. Biogas production was measured using Anaero BMP equipment and Arduino data logger (Anaerotechnology Ltd.).

STD_1 = Raw Slurry from holding tank 101- No Microwave [Control]

STD_2 = Digestate from AD 100 – No Microwave [Control]

M_1 = Raw Slurry from holding tank 101 Microwaved 100°C

M1_50 = Raw Slurry from holding tank 101 Microwaved 50°C

M_2 = Raw Slurry separated from holding tank 101 – No Microwave [Control]

M_2a = Raw Slurry separated from holding tank 101 Microwaved 100°C

M_3 = Digestate from AD 100 Microwaved 100°C

Effect of Microwave treatment on the availability of total and volatile solids

Pig slurry was processed continuously through the system 1, in which the residency time in the microwave reactor was 18 seconds for samples processed at 100°C and 10 seconds for samples processed at 50°C. Samples were then collected via the sampling line S shown in Fig. 8 and tests carried out in the laboratory to indicate effectiveness of the system.

As shown in Table 1 below, total solids analysis was performed in triplicate by heating at 105°C overnight and measuring weight until moisture was removed. Dry matter from triplicates was combined and placed in a muffle furnace at 550°C for 2 hours and weighed until organic matter was removed. Microwave treatment at 100°C increases the amount of total and volatile solids as a percentage of total solids of the microwave treated slurry samples compared to untreated slurry.

		Total Solids (g/L)	Volatile Solids (g/L)	Volatile Solids as % of Total Solids
STD_1	Raw Slurry from holding tank 101- No Microwave [Control]	18.1	11.0	61%
M1_50	Raw Slurry from holding tank 101 Microwaved 50°C	20.4	12.1	59%
M_1	Raw Slurry from holding tank 101 Microwaved 100°C	22.4	14.8	66%

Table 1: Effect of microwave treatment on total and volatile solid availability of pig slurry.

Impact of Temperature Rise to 100°C on the % sCOD.

In order to determine the improved level of biological degradability of the slurry processed through the system 1, total and soluble chemical oxygen demand (sCOD) tests were performed with target temperatures of 100°C (M1 & M3) and no microwave treatment (STD_1 & STD_2). COD is a standard method for measurement of the amount of pollution in sample water that cannot be oxidized biologically. Soluble COD determines the part of total COD that is biologically degradable or that can be oxidised. Table 2 below shows total COD (tCOD) and soluble COD (sCOD) for microwave treated slurry (M1, M3) and non-microwave untreated slurry (STD_1, STD_2) through the system 1. The % of COD that is soluble and thus biodegradable increases by 19% for undigested slurry raised to 100°C by microwave treatment

(M1) and by 21% for slurry that is already partly digested in the anaerobic digester 101 and raised to 100°C by microwave treatment (M3). This increased solubility enables the bacteria in the anaerobic digestion process to breakdown the organic waste more efficiently and thus generate greater amounts of biogas in a faster period of time.

Sample ID	tCOD (mg/l)	tCOD StdDev	sCOD (mg/l)	sCOD StdDev	% sCOD/tCOD	% change with microwave
STD_1 – Raw Slurry from holding tank 101- No Microwave [Control]	52.40	0.33	18.33	0.24	34.98	X
M1 – Raw Slurry from holding tank 101, Microwaved 100°C	39.10	1.93	21.13	3.30	54.04	19.06
STD_2 - Digestate from AD 100 – No Microwave [Control]	32.47	4.00	11.93	0.37	36.74	X
M3 – Digestate from AD 100 Microwaved 100°C	33.40	0.64	19.47	0.31	58.29	21.55

Table 2: Effect of sCOD results through the system 1 reactor 27

<u>Effect of microwave treatment on biogas production</u>

Pig slurry was processed continuously through the system. The residency time in the microwave reactor was 18 seconds for samples processed at 100°C and 10 seconds for samples processed at 50°C. Samples were then collected via the sampling line and tests carried out in the laboratory to indicate effectiveness of the system.

Fig. 9 illustrates the effect of microwave treatment on cumulative biogas production from slurry 101. Inoculum and substrates were placed in batch reactor vessels in triplicate and continuously mixed for 14 days. Biogas production was measured, calculated in mL per g of volatile solid and averaged for each sample. Results show that the most biogas was produced by microwaving raw slurry to 100°C (M_1). Raw slurry microwaved at 50°C (M1_50) has a faster rate of utilisation and biogas production however has a final yield comparable to untreated raw slurry (STD_1).

Fig. 10 illustrates the effect of microwave treatment on daily biogas production from slurry 101. Inoculum and substrates were placed in batch reactor vessels in triplicate and continuously mixed for 14 days. Biogas production per day was measured, calculated in mL per g of volatile solid and averaged for each sample. For untreated slurry most biogas is produced from Day 2 to Day 4, with peak biogas yield of ~30mL/gVS on Day 2. Slurry microwaved at 50°C produces a majority of biogas on day 2 with a peak of ~46mL/g VS, production gradually drops off to less than 10mL/gVS at Day 6. Slurry microwaved at 100°C produces a majority of biogas over a longer period of significant production between Day 1 and Day 7, with a peak of ~50mL/gVS on Day 5. From Day 5 biogas production gradually decreases to less than 10mL/gVS by Day 9.

<u>Effect of separation and microwave treatment on biogas production</u>

Pig slurry from holding tank 101 was pumped to the separator 22 at an input rate of approximately 25 litres per minute. Fig. 11 shows the effect of separation on cumulative biogas production of slurry 101. Inoculum and substrates were placed in batch reactor vessels in triplicate and continuously mixed for 14 days. Biogas production was measured, calculated in mL per g of volatile solids and averaged for each sample. Results show that the biogas yields for separated slurry (M_2) ~264mL/gVS are greater than yields for unseparated raw slurry (STD_1) ~143mL/gVS.

Fig. 12 shows the effect of separation on daily biogas production of slurry 101. Inoculum and substrates were placed in batch reactor vessels in triplicate and continuously mixed for 14 days. Biogas production was measured, calculated in mL per g of volatile solid and averaged for each sample. Separated slurry has a shorter lag time in comparison to unseparated slurry with peak biogas production of ~67mL/gVS on Day 1, separated slurry peaks on Day 2.

Fig. 13 shows the effect of separation and microwave treatment at 100°C on cumulative biogas production of slurry 101. Inoculum and substrates were placed in batch reactor vessels in triplicate and continuously mixed for 14 days. Biogas production was measured, calculated in mL per g of volatile solids and averaged for each sample. Results show that the biogas yields for slurry separated and microwaved at 100°C (M_2a) give the greatest biogas yield. Slurry treated with microwaving at 100°C (M_1) show similar biogas yield to those undergoing combination treatment. Slurry that has been separated (M_2) showed slower biogas production but had a final biogas yield within 100mL/gVS of those treated with microwaving at 100°C. All treated samples show a greater biogas production compared with untreated slurry (STD_1).

Fig. 14 shows the effect of separation and microwave treatment at 100°C on the daily biogas production of slurry 101. Inoculum and substrates were placed in batch reactor vessels in triplicate and continuously mixed for 14 days. Biogas production was measured, calculated in mL per g of volatile solid and averaged for each sample. Slurry separated and microwaved at 100°C (M_2a) showed a longer period of biogas production starting on Day 1 and only falling below 10mL/gVS on Day 9. This is a longer period of productivity in comparison to microwaving or separation alone

Fig. 15 shows the effect of treatment on total biogas production using the system 1, indicating total cumulative biogas (mL/gVS) production for slurry and digestate following a range of treatments. The greatest biogas production occurred in slurry (M1) treated from 101 at 100°C for 18 seconds and slurry separated (M2a) from 101 via separator 22 at a rate of approximately 25 litres per minute and treated for 18 seconds at 100°C. Treating digestate slurry from the anaerobic digester 100 did not lead to a significant increase in biogas production

Summary of effect of microwave treatment on biogas production

Mode	Flow Rate through MW reactor 27 (m3 per hour)	Residency time in MW reactor 27	HX 26 outlet temp., in prior to MW reactor 27	MW reactor 27 power (kW)	MW output temp (°C)	MW reactor Pressure	Total cumulative biogas (mL/gVS)	% increase in cumulative biogas (mL/gVS) vs control
STD_1 – Raw Slurry from holding tank 101- No Microwave [Control]	-	-	-	-	-	-	142.7	-
M1_50 - Raw Slurry from holding tank	0.8	10 seconds	40-55°C	18KW	100°C	0.5 – 4 bar	164.2	15%

101 Microwaved 50°C								
M1 – Raw Slurry from holding tank 101 Microwaved 100°C	0.5	18 seconds	40-55°C	18KW	100°C	0.5 – 4 bar	305.4	114%
M2a – Raw Slurry separated from holding tank 101 Microwaved 100°C	0.5	18 seconds	40-55°C	18KW	100°C	0.5 – 4 bar	323.8	127%

Table 3: Summary of flow, temp and biogas uplift from test results

Results show applying microwave radiation to unseparated slurry prior to anaerobic digestion using system 1 can increase biogas production over a 14 day period by 15% to 114%. The largest increase (114%) for unseparated material was observed when the biomass was heated to 100°C (M1). By increasing the microwave power above 18kW, quicker flow rates through the reactor 27 may be achieved. Microwaving separated slurry (M2a) produced even greater results compared to untreated unseparated slurry (127% increase in cumulative biogas) and is the optimum mode of operation of the system 1 for slurry, up to a certain point. A major consideration is the organic loading rate of the anaerobic digestion process. Continuously separating biomass into a liquid fraction and solid fraction, and then treating the solid fraction with microwaves before discharging to the anaerobic digester 100 will increase the organic loading rate (OLR). The OLR determines the optimum amount of volatile solids to be input on a daily basis. Optimum OLRs for anaerobic digestion differ for each type of biomass used in the process and thus the system 1 can be operated in different modes depending on the OLR requirements of the anaerobic digestion process.

The heat exchanger 26 prior to the microwave reactor 27 gives the feedstock an initial temperature rise. In most commercial anaerobic digestion plants, hot water is plentiful and often wastes as it has no immediate use. Using the system 1, the waste heat is utilised in the HX 26 as part of the process. 50°C to 90°C heat entering the HX 26 increases the feedstock temperature to the microwave reactor 27 and thereby increases the efficiency.

The temperature rise in the microwave reactor 27 is only significant for flow rates of less than 0.3m^3 per hour for 18kW power consumption of the reactor 27. However, for higher power operation at 36kW, significant temperature rises (greater than 50°C) is achieved. The microwave reactor power can be increased by the power supply 48 to at least 150kW for treatment processes requiring higher flow rates than tested.

The system 1 adjusts the flow rate to ensure that the biomass is heated to the optimal temperature in the microwave reactor 27. Based on the type of biomass and the optimal heating temperature (set in the controller 20) the pump 35 is configured to ensure flow rate and residency time in the microwave reactor 27 achieve the optimal temperature.

Feedback from the pressure sensors is used by the controller to maintain structural integrity of the system. If the pressure rises above 6 Bar in this example, the microwave energy to the reactor 27 will be temporarily stopped until the pressure reduces to an acceptable level. The controller 20 monitors the reflected power within the microwave reactor 27. If the reflected power rises above a certain level (user-defined) the microwave energy to the reactor 27 is temporarily stopped until the reflected power reduces to an acceptable level. The controller 20 can be operated remotely via cloud-based monitoring and control system.

The heat exchanger 26 may utilise waste heat from the AD tank 100 thus providing for a cost-effective means of raising the initial temperature of the biomass prior to the microwave phase. Preferably, the microwave reactor 27 is insulated to ensure maximum thermal efficiency. Preferably the tube (not shown) within the microwave reactor 27 is constructed with pyrex, quartz, PTFE or a ceramic material.

Preferably the microwave reactor 27 has a stirring mechanism to provide maximum homogeneousness of the biomass and to reduce the existence of “hot spots” in the microwave reactor. The stirring device is preferably made of, or coated in, PTFE or a similar material. A second microwave reactor may be placed adjacent to the existing reactor to increase throughput.

The hopper 25 volume is between 1 and 2 m^3 but can be configured to be bigger or smaller within the confines of the container (no.1).

Alternative Examples

In other examples, the system includes a heat exchanger after the microwave reactor. This can be controlled to vary temperature for more efficient AD treatment. In particular the temperature may be adjusted by such a heat exchanger to 30°C to 60°C.

The separator 22 is preferred, but optional. Also, a chiller is optional – not required for certain microwave generator types.

The system may not be modular, and even where it is modular it need not necessarily be in the form of a container for transport. Indeed, the system may be incorporated in a continuous process system in a fixed treatment plant. Where this is the case, the processing parameters described above apply. In such a system the heat exchanger upstream of the microwave reactor may be arranged to receive material directly from an upstream component, possibly be direct piping.

Where the system is modular it may not have a cover for the separator. This may alternatively be achieved by rearranging the separator to fit entirely in the container or to be removed entirely.

In another example, there may be a heat exchanger cooler to cool the feedstock delivered from the microwave reactor 27 and before delivery to the AD 100. The desired temperature will typically be 30°C to 60°C in order to reduce the temperature of the treated material to that of the biomass already residing in the anaerobic digester. The heat created in this cooler could be utilised to pre-heat untreated biomass going directly to the anaerobic digester.

The controller 20 may be distributed, and may for example include a cloud-based host server.

The hopper may include a mixer of type paddle or a shredder in order to improve uniformity of the feedstock which is pumped through the HX 26 and the reactor 27.

Advantages

It will be appreciated that the system achieves more economical processing of feedstocks such as animal slurry, without need for other feedstocks for co-digestion. The invention achieves a greater production of biogas such as methane at a higher quality from a given amount of solids. It is also improves digestibility of feedstock to allow a more rapid conversion of carbon in a shorter time, with reduced processing time in the AD. It also achieves improved versatility in treatment of waste materials. Also, it reduces capital cost and operating expenses for AD processing. Also, the invention provides for continuous operation, reduced odour in digestate, more effective destruction of pathogens that might be harmful, and reduce particle size of digestate solids.

The expectation was about a 40% increase in gas production, but results showed 15% to 127% increase by adopting flow, pressure, microwave power, and in some cases separation of biomass into solid fraction for treatment, as described in table 3. It was thought that the temperature of the biomass needed to reach 140°C for a 40% biogas production increase to be achieved, however it was possible to get a much higher increase at a lower than expected temperature i.e. about 100°C. Also, we have found increased sCOD by 14 to 21% where there is both separation and microwave treatment.

Types of biomass which can be processed through the system include dairy processing waste, waste water, agriculture by-products such as slurries, agricultural crops such as grass, maize etc., slaughterhouse waste, distillation waste water and draff, food and vegetable waste.

The invention is not limited to the embodiments described but may be varied in construction and detail.

Claims

1. A biomass treatment system (1) comprising:
   a separator (22),
   a microwave reactor (27),
   a pump (35) arranged to deliver solids output from the separator to the microwave reactor, and
   a reactor outlet (28) with a valve, arranged to delivery outlet feedstock to an anaerobic digester, and
   a controller (20) configured to control the separator to provide feedstock with a desired solids content to the microwave reactor and to control the microwave reactor for desired treatment of said feedstock for subsequent downstream anaerobic digestion,
   wherein the system comprises a feedstock direct intake (25) separate from the separator (22), and interfaces (7, 21) arranged to receive feedstock into the direct intake or into the separator, both being linked with the microwave reactor (27),
   couplers (21, 28, 24) for coupling the treatment system to an external anaerobic digester (100-103) to provide a combined system.

2. A treatment system as claimed in claim 1, wherein the separator (22) is arranged to deliver a solids portion into said direct intake (25).

3. A treatment system as claimed in claims 1 or 2, wherein the system (1) comprises a housing (2) which is transportable for modular coupling to an external anaerobic digester.

4. A treatment system as claimed in claim 3, wherein the housing is of box rectangular shape.

5. A treatment system as claimed in any of claims 1 to 4, wherein the separator (22) is linked with a coupler (21) to receive partially digested feedstock from an anaerobic digester.

6. A treatment system as claimed in any preceding claim, wherein the separator (22) is linked with a coupler (24) to deliver a liquid portion to an external tank (103) or anaerobic digester.

7. A treatment system as claimed in any preceding claim, wherein the couplers (21, 7) are arranged to receive feedstock into either the separator (22) or the direct intake (25).

8. A treatment system as claimed in any preceding claim, wherein the system comprises a heat exchanger (26) linked with an inlet of the microwave reactor (27).

9. A treatment system as claimed in claim 8, wherein the heat exchanger (26) is linked to receive feedstock from both the separator and to the direct inlet.

10. A treatment system as claimed in claim 9, wherein the heat exchanger (26) is directly linked to the direct inlet and is linked via the direct inlet (7, 25) to the separator.

11. A treatment system as claimed in any preceding claim, wherein the direct inlet comprises a hopper (25).

12. A treatment system as claimed in any of claims 8 to 11, wherein the heat exchanger comprises (49) couplers for linking to a hot water supply such as that from a boiler fed by biogas.

13. A treatment system as claimed in any of claims 8 to 12, wherein the heat exchanger and the controller are arranged to increase temperature of feedstock to a value in the range of 30°C to 80°C.

14. A treatment system as claimed in any preceding claim, wherein the system comprises at least one valve (45, 46) downstream of the reactor and being operatively linked with the controller (20) to control residency time and/or temperature within the reactor.

15. A treatment system as claimed in claim 14, wherein there are a plurality of valves (45, 46) downstream of the reactor, and the controller (20) is configured to operate only one of said valves at any one time.

16. A treatment system as claimed in any preceding claim, wherein the microwave reactor (27) has a vertical orientation with a vertical tube for conveying feedstock, and a microwave generator with a waveguide arranged to direct radiation transversely across the tube.

17. A treatment system as claimed in any preceding claim, wherein the separator (22) comprises a vibratory mesh which is oriented with an acute angle of less than 45° to vertical and is curved downwardly and outwardly with an enlarging angle to vertical, in which a liquid component is directed to fall through mesh apertures to a coupler for an external anaerobic digester, and a solids portion slides downwardly over the mesh and into a hopper (25) linked with the microwave reactor inlet.

18. A treatment system as claimed in any of claims 8 to 17, wherein the heat exchanger comprises feedstock-conveying tubes surrounded by an air jacket, and scrapers arranged to clean the tube internal surfaces.

19. A treatment system as claimed in any preceding claim, further comprising a heat exchanger to cool feedstock for an external anaerobic digester, and in which the controller (20) is configured to control said heat exchanger with temperature feedback from an external anaerobic digester to ensure that the temperature within the anaerobic digester does not rise to greater than an upper threshold.

20. A treatment system as claimed in any preceding claim, wherein the controller (20) is configured to operate in one or more modes of operation, said modes differing according to nature of feedstock and/or paths through the system.

21. A treatment system as claimed in claim 20, wherein a mode is for untreated biomass such as slurry directly to the direct intake (7, 25) and which is pumped to the microwave reactor (27).

22. A treatment system as claimed in claims 20 or 21, wherein a mode is for untreated biomass such as slurry fed to the separator (22).

23. A treatment system as claimed in claims 20 or 21 or 22, wherein a mode is for treated biomass fed directly (21) to the direct intake (7) and which is fed back to the microwave reactor (27).

24. A treatment system as claimed in any of claims 20 to 23, wherein a mode is for treated biomass fed (21) to the separator (22).

25. A treatment system as claimed in any of claims 20 to 24, wherein the controller is configured to process with a selected mode according to a desired volume of feedstock received.

26. A treatment system as claimed in any of claims 20 to 25, wherein the controller (20) is configured to automatically start a wash (150) cycle for at least some components and pipes upon completion of a mode for a set volume.

27. An anaerobic digestion system comprising a treatment system of any preceding claim coupled to an anaerobic digester (100-103), and pumps arranged to deliver feedstock from the microwave reactor to the anaerobic digester.

28. An anaerobic digester system as claimed in claim 27, wherein:

the separator (22) is linked with a coupler (21) to receive partially digested feedstock from the anaerobic digester,

the separator (22) is linked with a coupler (24) to deliver a liquid portion to the anaerobic digester,

the couplers (21, 7) are arranged to receive feedstock into either the separator (22) or the direct intake (25), and

the system comprises a heat exchanger (26) linked with an inlet of the microwave reactor (27), and the heat exchanger (26) is linked to receive feedstock form both the separator and to the direct inlet, the heat exchanger (26) is directly linked to the direct inlet and is linked via the direct inlet (7, 25) to the separator.

29. An anaerobic digester system as claimed in claim 28, wherein the system comprises a heater powered by biogas from the anaerobic digester, and said water heater is linked with the heat exchanger to supply the heat exchanger with water in a temperature range of 50°C to 90°C for pre-heating of feedstock before the microwave reactor (27).

30. A method of operation of a system of either of claims 28 or 29, the method comprising:
    delivering a biomass feedstock to the separator (22),
    the separator separating the feedstock into a solids fraction and a solids fraction,
    feeding the liquid fraction to an outlet (24),
    feeding the solids fraction to the heat exchanger (26),
    the heat exchanger (26) pre-heating the feedstock,
    pumping the pre-heated feedstock to the microwave reactor (27),
    the microwave reactor (27) treating the feedstock by elevating temperature of the feedstock, and
    delivering the treated feedstock to an anaerobic digestion system (100).

31. A method as claimed in claim 30, wherein the feedstock delivered (21) to the separator (22) includes digestate from the anaerobic digestion system (100).

32. A method as claimed in claim 31, wherein the heat exchanger (26) supplies thermal energy (49) to the feedstock derived from biogas generated by the anaerobic digestion system (100).

33. A method as claimed in any of claims 30 to 32, wherein the separator (22) provides a solids fraction with a solids content of the range of 8% to 30% dry matter.

34. A method as claimed in any of claims 30 to 33, wherein the heat exchanger (26) elevates temperature of the solids fraction to a value in the range of 30°C to 80°C.

35. A method as claimed in any of claims 30 to 34, wherein the microwave reactor elevates the feedstock temperature to a value in the range of 30°C to 150°C during a ramp-up time duration of up to 20 seconds.

36. A method as claimed in any of claims 30 to 35, wherein the pressure in the microwave reactor is in the range of 0.5 Bar to 6 Bar.

37. A method as claimed in any of claims 30 to 36, wherein the pressure in the microwave reactor is controlled by control of pressure valves (45, 46) downstream of the reactor and by control of a pump (35) for delivering the solids fraction to the reactor.

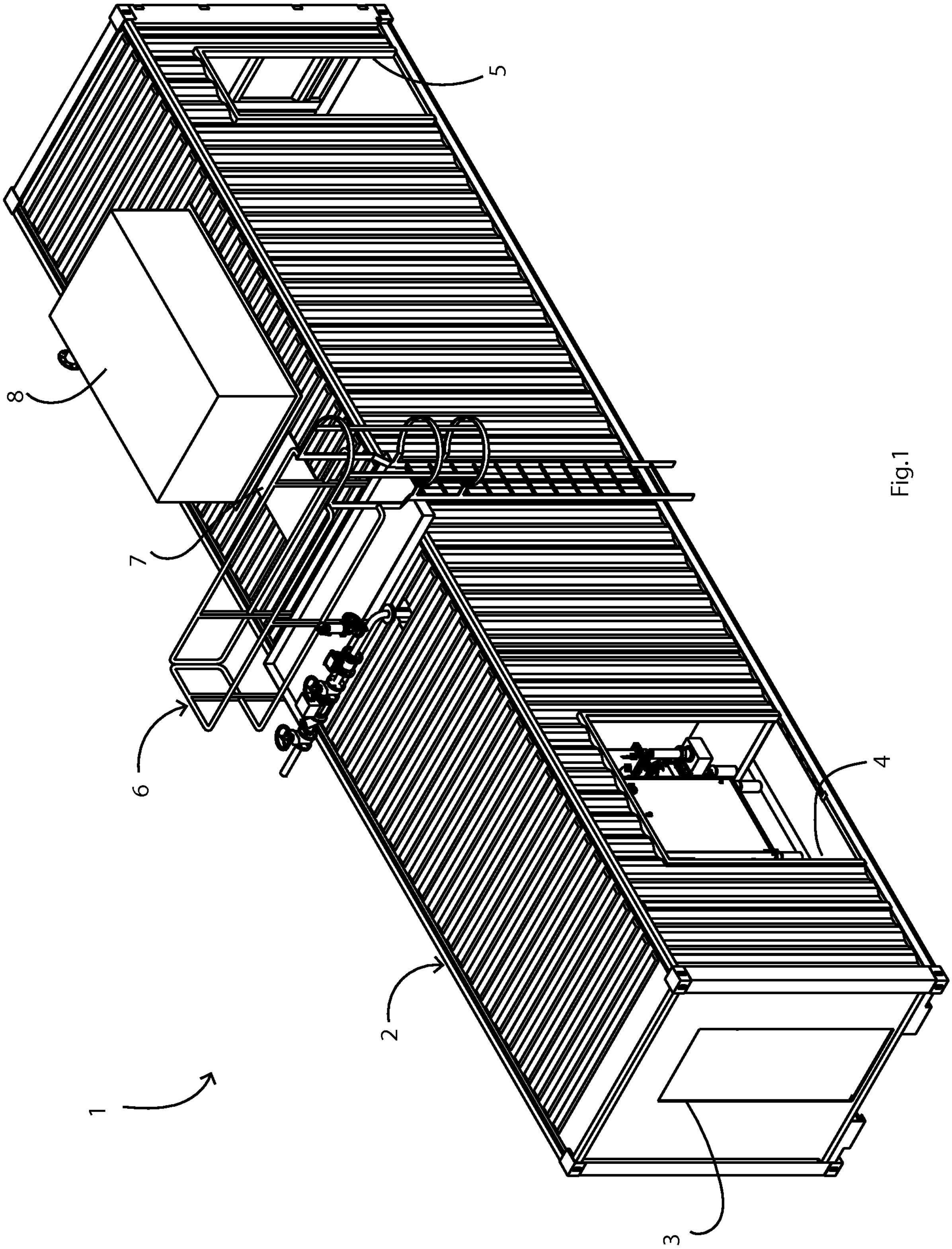


Fig.1

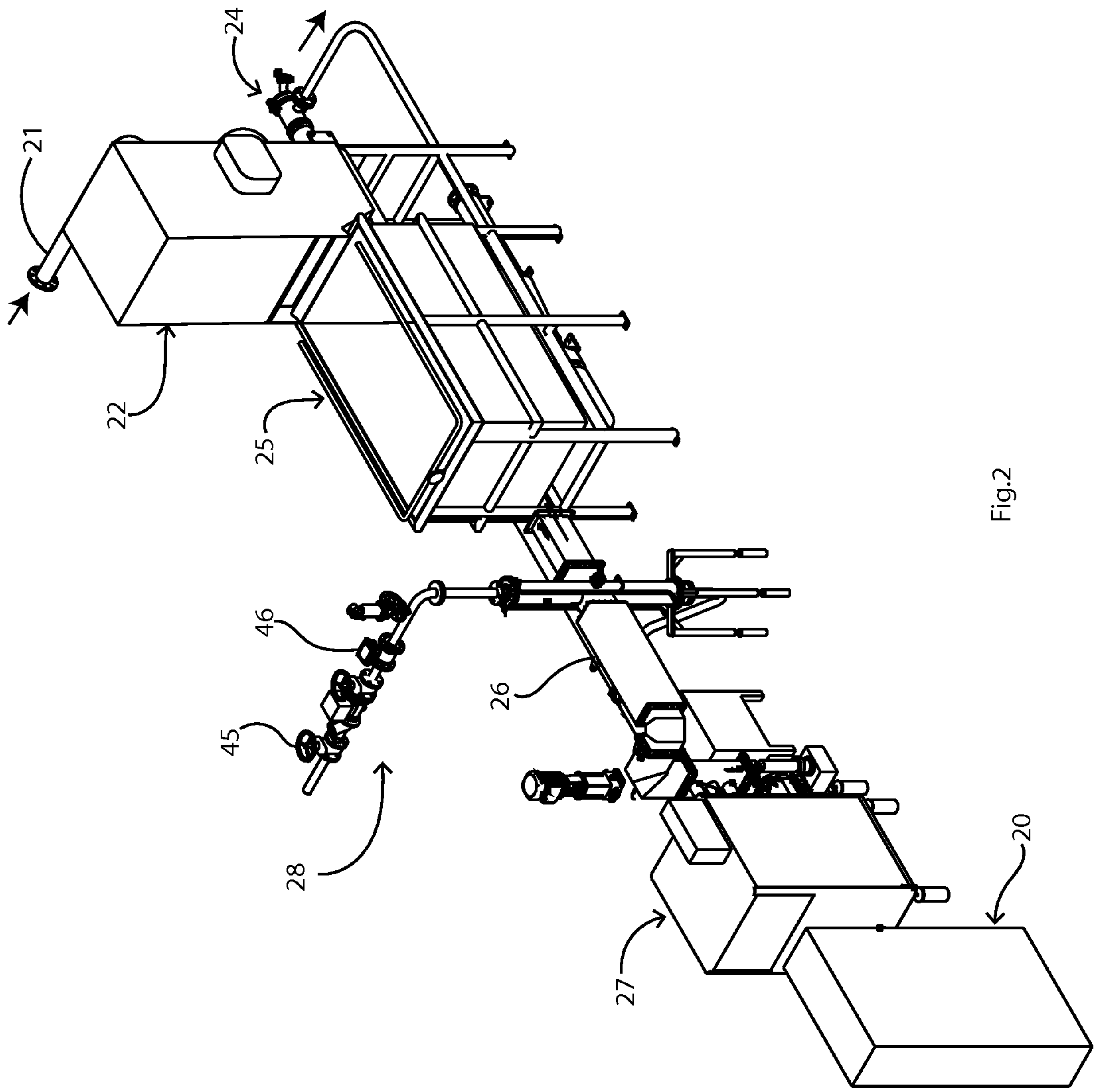


Fig.2

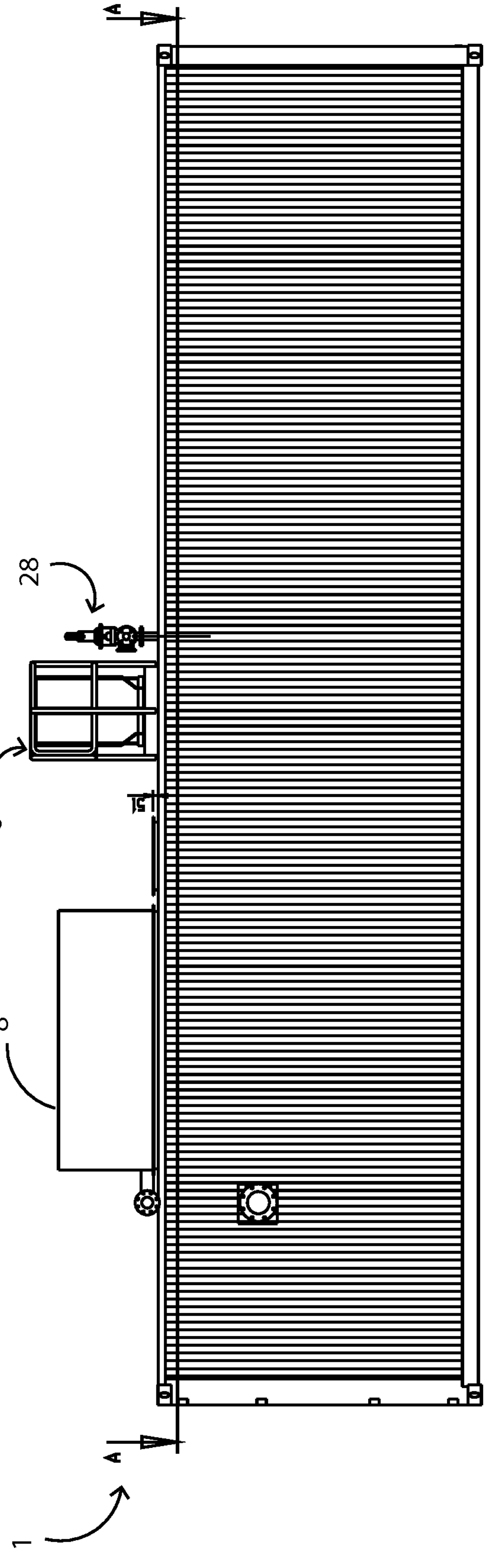


Fig.3

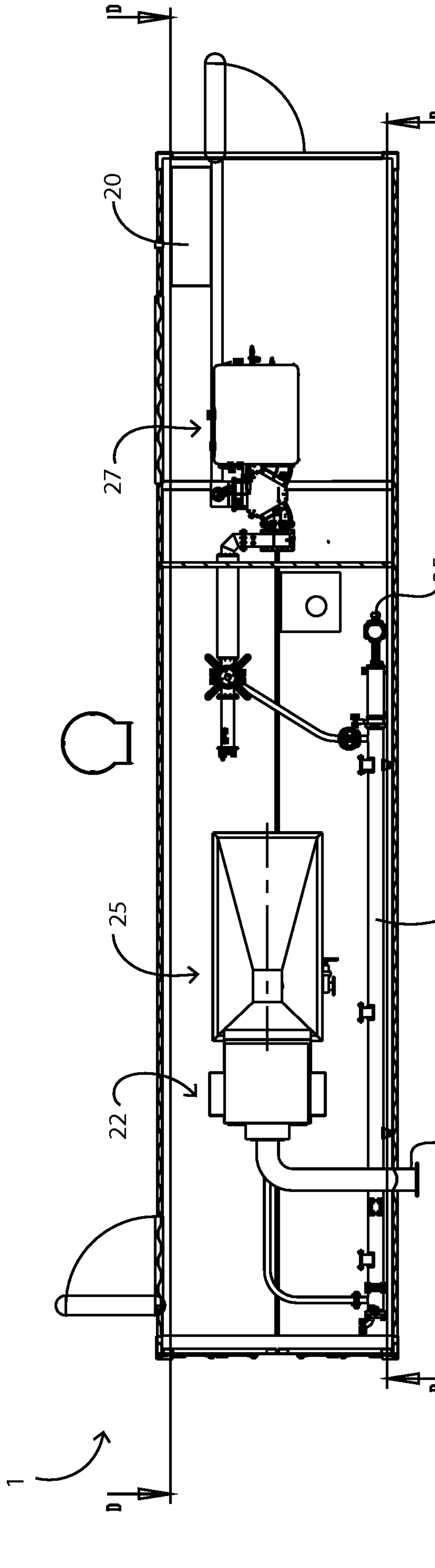


Fig.4

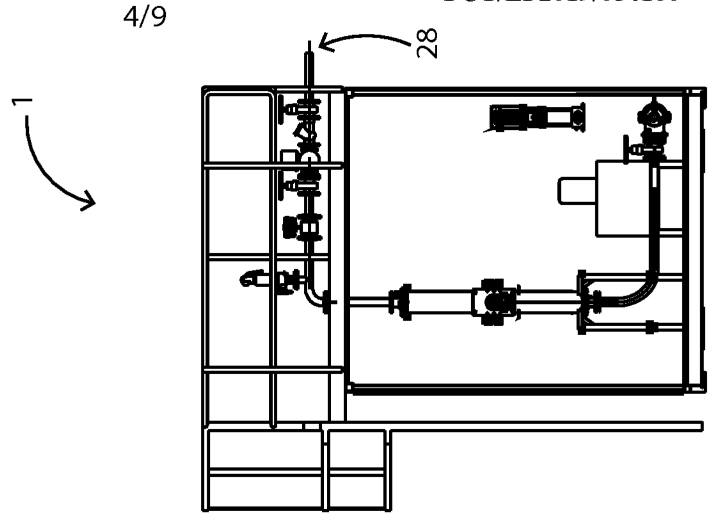


Fig.7

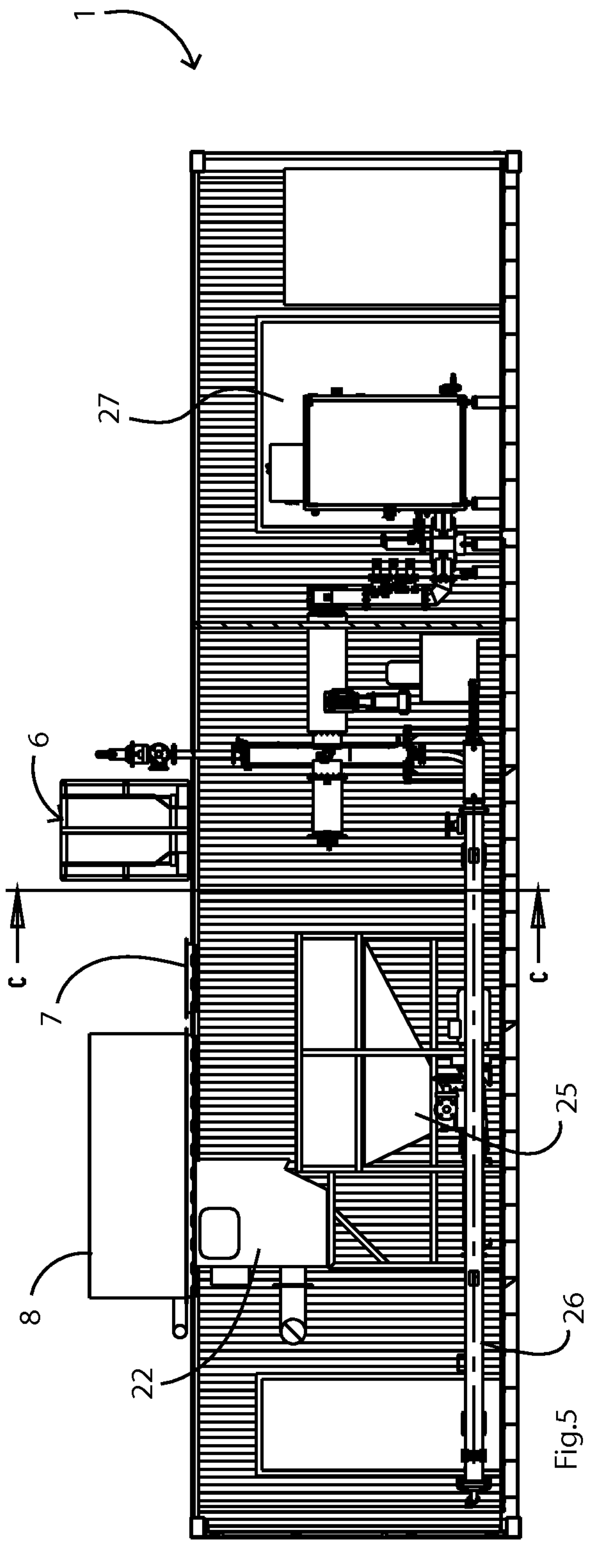


Fig.5

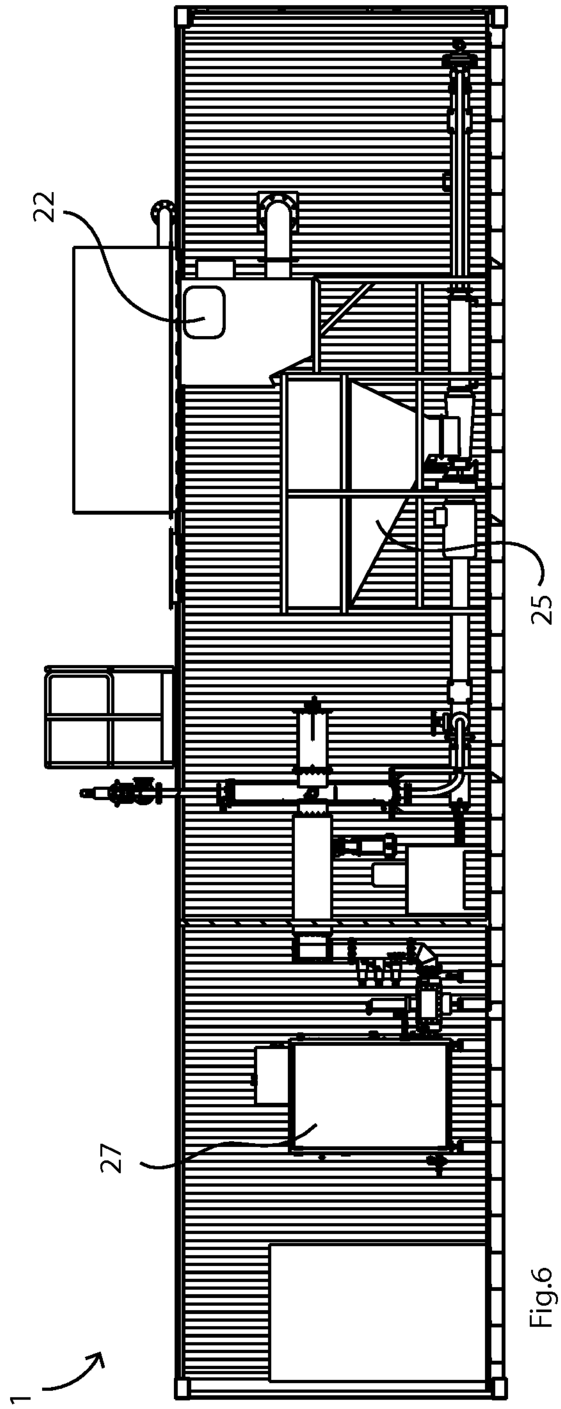
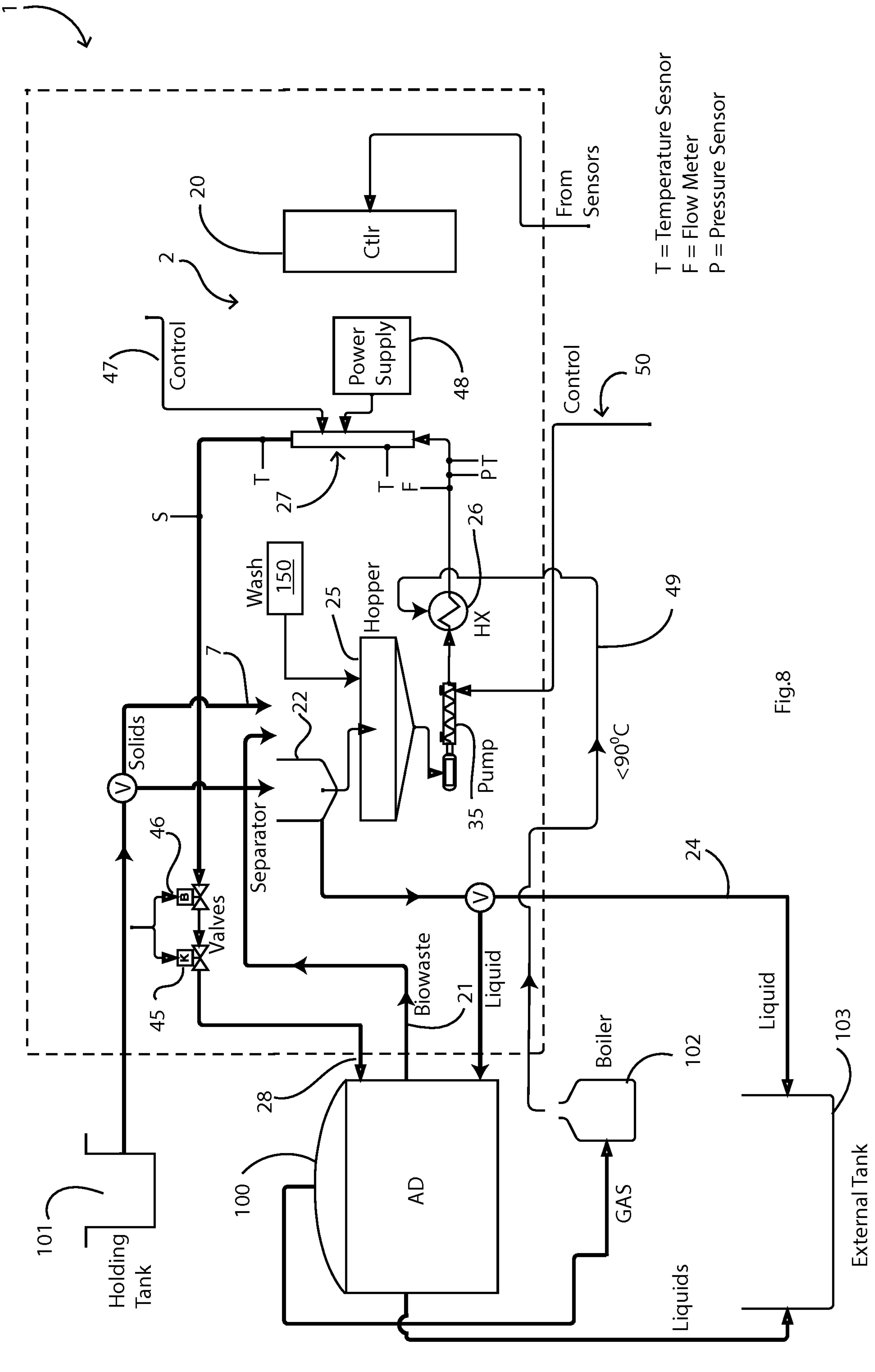


Fig.6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2
20
Ctlr
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F = Flow Meter
P = Pressure Sensor
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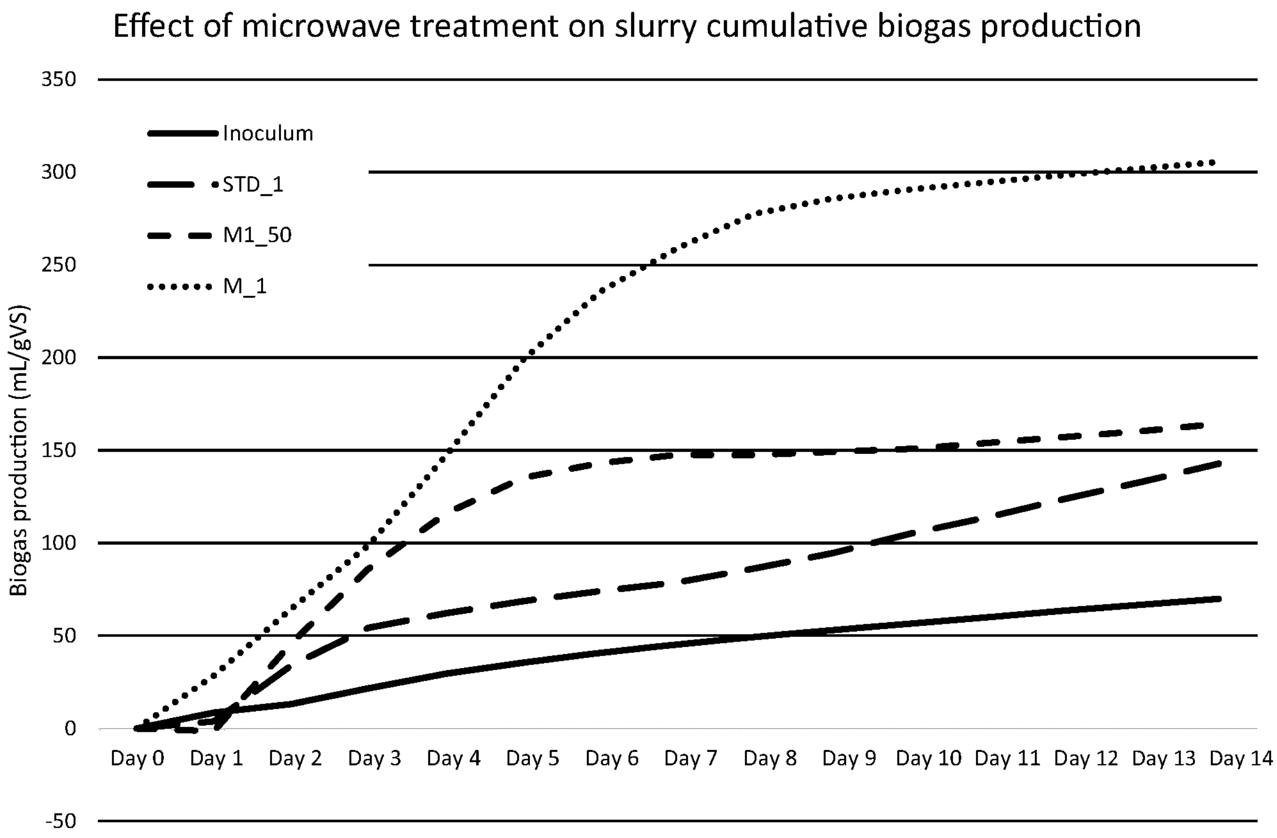
Control
Power Supply
48
Control
50
S
T
27
T
F
PT
26
Wash
150
25
Hopper
HX
49
7
22
Solids
V
Separator
Pump
35
<90^{0}C
46
B
Valves
K
45
Biowaste
21
Liquid
V
24
Liquid
28
100
AD
101
Holding Tank
Boiler
102
GAS
Liquids
103
External Tank

Fig.8


Effect of microwave treatment on slurry cumulative biogas production
Biogas production (mL/gVS)
350
300
250
200
150
100
50
0
-50
Inoculum
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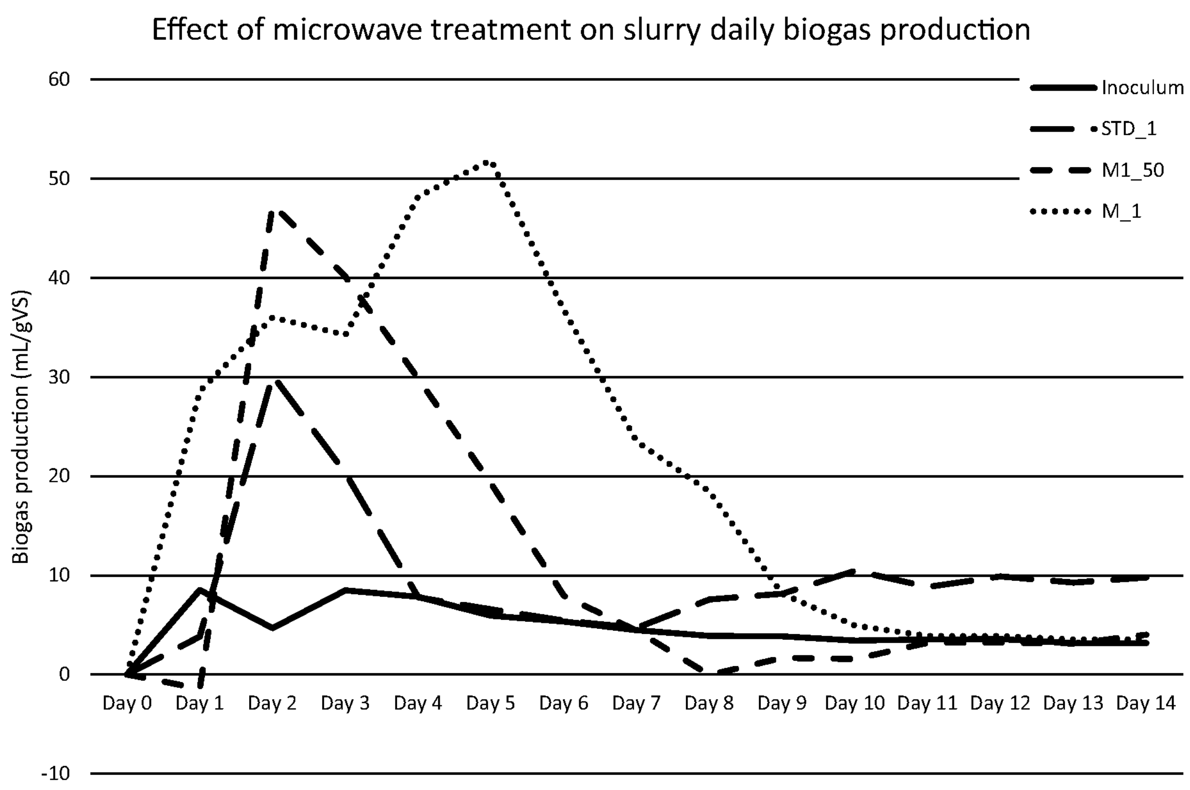
M1_50
M_1
Day 0 Day 1 Day 2 Day 3 Day 4 Day 5 Day 6 Day 7 Day 8 Day 9 Day 10 Day 11 Day 12 Day 13 Day 14

Fig.9


Effect of microwave treatment on slurry daily biogas production
Biogas production (mL/gVS)
60
50
40
30
20
10
0
-10
Inoculum
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M1_50
M_1
Day 0 Day 1 Day 2 Day 3 Day 4 Day 5 Day 6 Day 7 Day 8 Day 9 Day 10 Day 11 Day 12 Day 13 Day 14

Fig.10

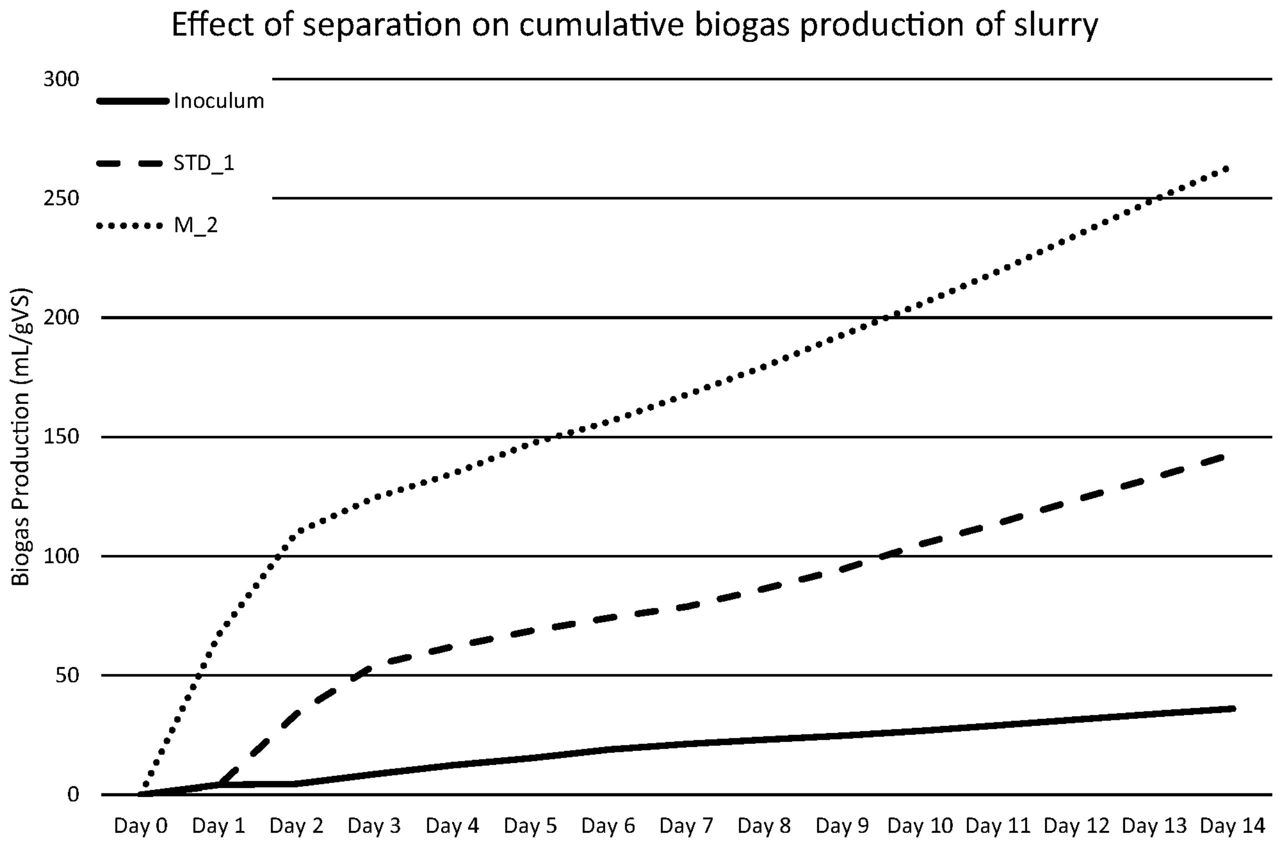
Effect of separation on cumulative biogas production of slurry
300
250
200
150
100
50
0
Inoculum
STD_1
M_2
Biogas Production (mL/gVS)
Day 0
Day 1
Day 2
Day 3
Day 4
Day 5
Day 6
Day 7
Day 8
Day 9
Day 10
Day 11
Day 12
Day 13
Day 14

Fig.11

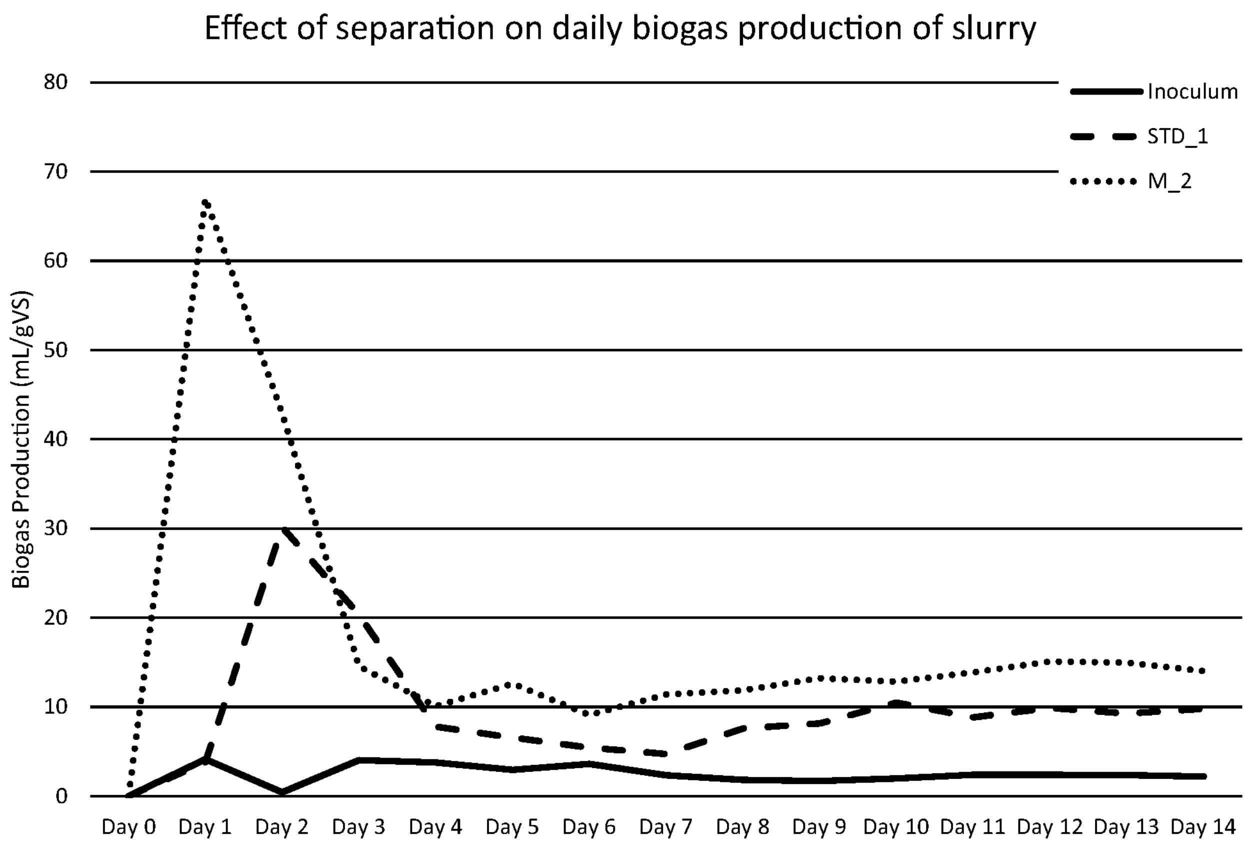
Effect of separation on daily biogas production of slurry
80
70
60
50
40
30
20
10
0
Inoculum
STD_1
M_2
Biogas Production (mL/gVS)
Day 0
Day 1
Day 2
Day 3
Day 4
Day 5
Day 6
Day 7
Day 8
Day 9
Day 10
Day 11
Day 12
Day 13
Day 14

Fig.12

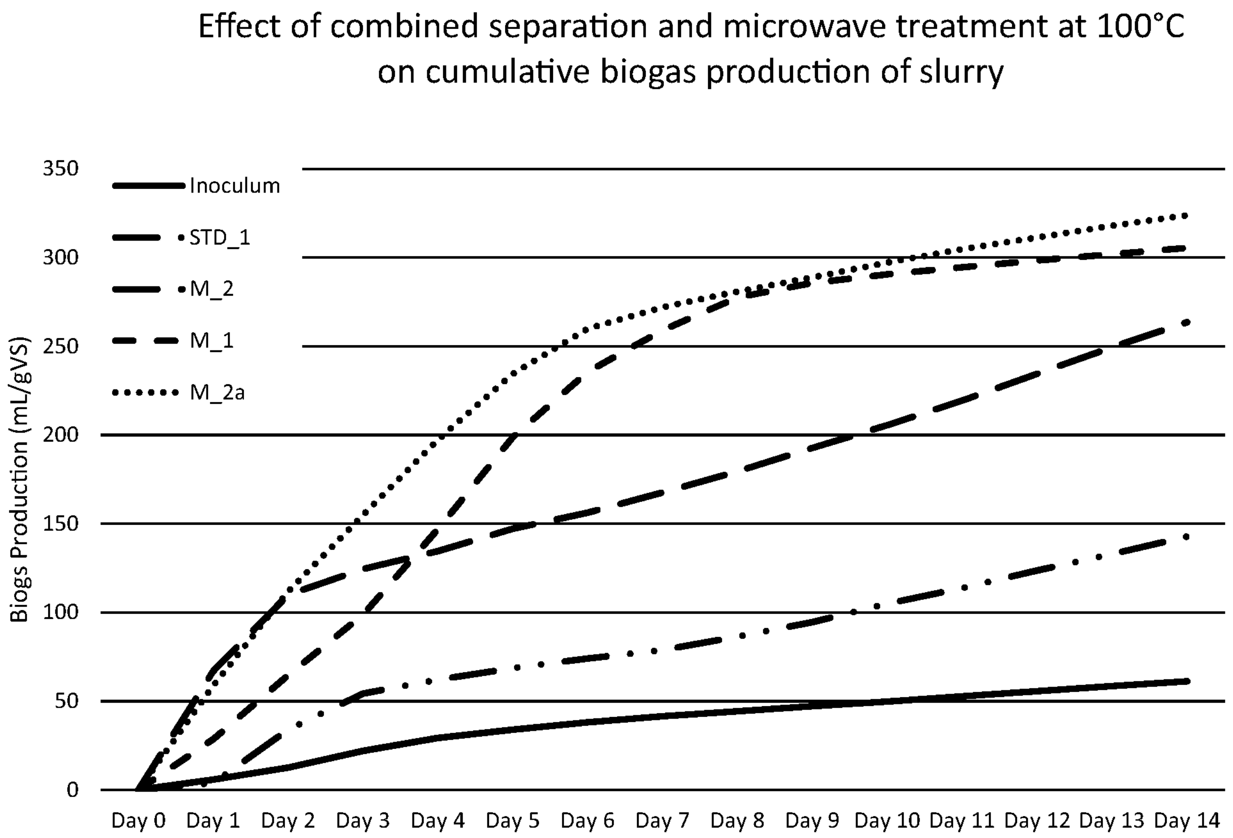
Effect of combined separation and microwave treatment at 100°C on cumulative biogas production of slurry
Biogs Production (mL/gVS)
0
50
100
150
200
250
300
350
Inoculum
STD_1
M_2
M_1
M_2a
Day 0
Day 1
Day 2
Day 3
Day 4
Day 5
Day 6
Day 7
Day 8
Day 9
Day 10
Day 11
Day 12
Day 13
Day 14

Fig.13

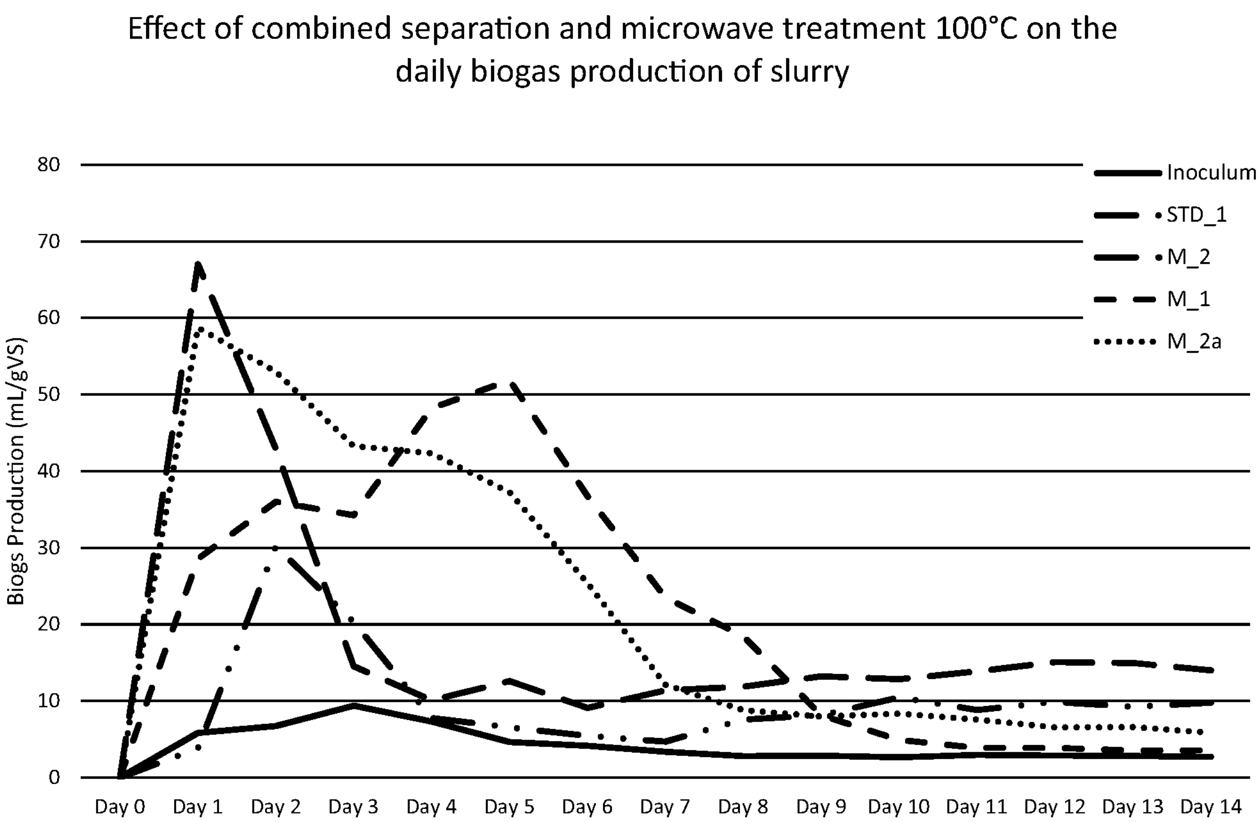
Effect of combined separation and microwave treatment 100°C on the daily biogas production of slurry
Biogs Production (mL/gVS)
0
10
20
30
40
50
60
70
80
Inoculum
STD_1
M_2
M_1
M_2a
Day 0
Day 1
Day 2
Day 3
Day 4
Day 5
Day 6
Day 7
Day 8
Day 9
Day 10
Day 11
Day 12
Day 13
Day 14

Fig.14

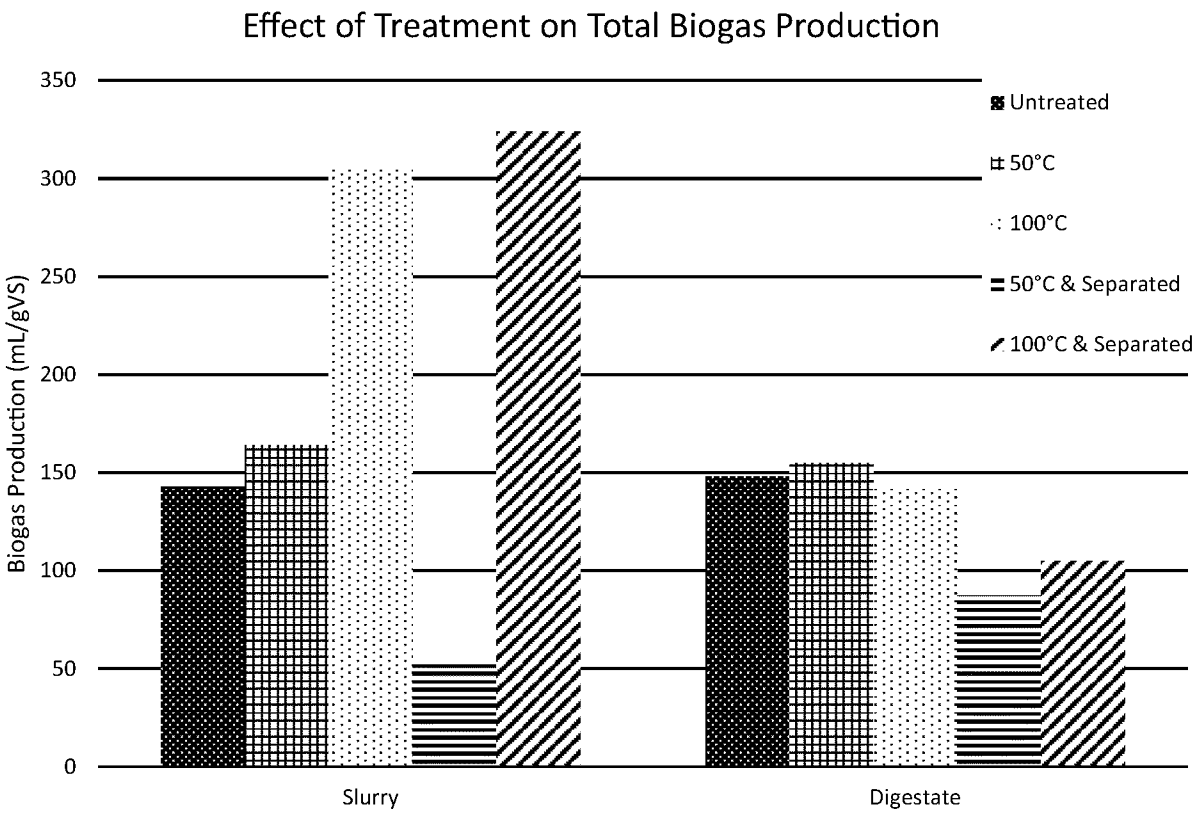
Effect of Treatment on Total Biogas Production
Biogas Production (mL/gVS)
350
300
250
200
150
100
50
0
Untreated
50°C
100°C
50°C & Separated
100°C & Separated
Slurry
Digestate

Fig.15

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2019/054160

A. CLASSIFICATION OF SUBJECT MATTER
INV. C12M1/107 C12M1/00
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
C12M C02F C12F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y	US 2017/088803 A1 (KNOOP ROBERT [US]) 30 March 2017 (2017-03-30) paragraphs [0036], [0037], [0047], [0048], [0056], [0073], [0077] - [0086] figures 4,6,7,8 -----	1,2,5-37 4
X A	US 2011/243802 A1 (RINGHEIM DANIEL [SE] ET AL) 6 October 2011 (2011-10-06) paragraphs [0020] - [0034] figures 1,2 -----	1,3,5 2,4,6-37
X A	US 2004/187534 A1 (GENIER REJEAN [CA]) 30 September 2004 (2004-09-30) paragraphs [0010] - [0015], [0042] - [0044], [0054] figures 6-11 -----	1 2-37
	-/--	

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

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"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
14 May 2019	22/05/2019

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Baumlin, Sébastien

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Form PCT/ISA/210 (second sheet) (April 2005)

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

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Y	US 2012/152812 A1 (PARK CHUL [US] ET AL) 21 June 2012 (2012-06-21) claims 1,2 pages 2,3 -----	4
A	EP 1 978 086 A1 (STIRL ANLAGENTECHNIK GMBH [DE]) 8 October 2008 (2008-10-08) cited in the application paragraphs [0050] - [0052], [0055] figures 1-3 -----	1-37
A	HOUTMEYERS SOFIE ET AL: "Comparing the influence of low power ultrasonic and microwave pre-treatments on the solubilisation and semi-continuous anaerobic digestion of waste activated sludge", BIORESOURCE TECHNOLOGY, ELSEVIER, AMSTERDAM, NL, vol. 171, 13 August 2014 (2014-08-13), pages 44-49, XP029067359, ISSN: 0960-8524, DOI: 10.1016/J.BIORTECH.2014.08.029 the whole document -----	1-37

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2019/054160

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