

Methods, systems and process equipment for optimized control of thermal hydrolysis processes

FIELD OF THE INVENTION

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The present invention relates to methods, systems, process equipment and plants useful in the context of subjecting biomass material, having a dry-matter content (DS%) of at least 8%, preferably at least 12%, to thermal hydrolysis processes (THP) and subsequent processing in the form of e.g. anaerobic fermentation, thermal
10 reduction, biological, chemical or electrochemical processing or the like. The present invention also relates to methods for retrofitting existing plants employing Thermal Hydrolysis Processes (THP).

BACKGROUND OF THE INVENTION

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Thermal hydrolysis is a process, which involves treating a wet or moist material, e.g. a biomass material, at elevated temperature followed by rapid decompression. In waste treatment industry such a combination of process steps is often referred to as a thermal hydrolysis process (THP). The application of THP is not limited to pre-
20 treatment of organic materials prior to biological downstream treatment, e.g. anaerobic digestion or fermentation for production of biogas or bio-ethanol, respectively, but can be also used in connection with non-biological downstream processing, for instance, for the production of fuel-pellets from lignocellulosic material or for the further extraction and production of added value compounds, such as amino acids, peptides
25 proteins, short chain fatty acids, enzymes, pesticides, bio-plastics, bio-flocculants and bio-surfactants.

Thermal Hydrolysis Processes (THP) may be designed for either batch or continuous mode. The methods, systems, process equipment and plants of the present invention
30 are relevant for both THP designed for batch and THP designed for continuous mode. Furthermore, the methods of the present invention can both be integrated in new plants and implemented into existing plants by retrofitting, involving installing relevant additional equipment and making relevant modifications.

35 In a THP the material is treated with a desired partial pressure of steam. In a batch process, the time the material is kept at the desired conditions is referred to as

“retention time”. For a continuous process, the overall average retention time is a value, which can be calculated from the overall through-put of the overall process.

5 The material will experience a rapid pressure reduction and undergo steam-explosion as it is discharged from the THP system, e.g. through a nozzle, to a flashtank. This opens cell walls, disintegrates organic materials, reduces particle sizes and apparent viscosity, e.g. the static yield stress, τ_o , and/or the dynamic yield stress, τ_y , of the material. The flash-steam resulting from the steam-explosion can be used to pre-heat material in a pressure vessel that can be referred to as a pulper. The use of flash-
10 steam to pre-heat material prior to reactor treatment is important for achieving the highest possible energy efficiency and the lowest possible steam consumption.

The general technology behind THP is described in great details in e.g. WO/1996/009882 and WO/2008/026932. Thus, material is first pre-heated from
15 ambient temperature with flash steam resulting from at least one subsequent pressure reduction step. Pre-heated material is then transferred to a (thermal hydrolysis) reactor where pressure increases up to 2.7-26 bar, e.g. by means of live steam injection as described in WO/1996/009882. In certain situations, this will correspond to temperatures up to 226°C. In most cases, however, the temperature will be within a
20 certain somewhat lower range as overheating may lead to undesirable changes in chemical composition of the material. On the other hand, as the desired effect of THP is also not achieved at too low temperatures, the preferred temperature for a THP process/System is typically in the range of 130-200°C for materials like municipal and industrial sludge qualities. However, more elevated temperatures may be beneficial for
25 several other materials or to achieve certain benefits. After a certain period, the material is rapidly discharged from the (thermal hydrolysis) reactor, e.g. through one or more blowdown conduits, to a pressure relief vessel, which is also sometimes referred to as flash tank.

30 The methods described in e.g. WO/1996/009882 and WO/2008/026932 are batch methods, however, e.g. WO/2000/73221 and EP3156374 describes continuous THP methods for the hydrolysis of organic material.

WO/2011/006854 describes yet another batch process for THP, which, via the use of a
35 nozzle by which the sludge can be transferred to a first pressure relief tank, i.e. flash tank, mitigates the need for a pressure relief of the thermal hydrolysis reactor as such.

Compared to the methods above, WO/2014/123426 describes a method and equipment for carrying out THP in which vacuum is provided in the hydrolysis reactor by supplying cold water to the hydrolysis reactor and opening a supply valve between the preheating tank and the reactor, whereby heated organic material can be

5 transferred from the preheating tank to the reactor with the help of a vacuum and gravity up to a predetermined level.

WO2015/097254 describes methods for the continuous thermal hydrolysis of a biomass material having a high dry matter content, in which the apparent viscosity of

10 the material is reduced upstream the thermal hydrolysis by subjecting it to a) a high-speed gradient (i.e. high shear strain) in a so-called dynamic mixer, which mechanically de-structures, i.e. breaks down, the material, and b) heating it by passing it through a heat exchanger in which heat is recovered directly from the hydrolysed sludge (i.e. without using any intermediate heat-carrying fluid).

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WO/2016/066752 describes THP methods in which the hydrolysed material is mixed with part of the content of a downstream digestion tank, via the use of a recirculation loop, before this mixture enters the digestion tank.

20 WO/2020/126397 describes THP methods involving flashing below ambient pressure and using the resulting flash steam for direct steam injection to pre-heat incoming feed in a pre-heating vessel maintained below ambient pressure to facilitate the flash steam transfer. The methods rely on maintaining parts of the system below ambient pressure by removing non-condensable gases by using a vacuum system and a minimum of

25 two pulpers and one flashtank upstream of the thermal hydrolysis reactor.

As should be clear from the above several improved THP methods, for both batch and continuous mode, have been developed in the prior art, which are each aimed at 1) making THP processes more versatile, e.g. as regards materials having a high dry

30 solid content, 2) reducing the overall energy consumption of THP processes and/or 3) improving, the quality and/or nature of the resulting hydrolysed material thereby enabling a simplification of downstream processing and ultimately the use of standard equipment for both the THP as such and downstream processing units.

35 Up to now, however, none of these improvements have, in contrast to the present invention, related to making systematic use of the relationship between the temperature and the apparent viscosity, e.g. the static yield stress, τ_0 , and/or dynamic

yield stress, τ_y , of the biomass material being processed at the various stages of a THP process, and the importance thereof in relation to optimizing and stabilising the flow of non-Newtonian biomass material having a relatively high dry-matter content (DS%), such as above 8%, preferably at least 12%, through a THP process with

5 regards to ensuring both a more efficient and stable THP process as such, but also more efficient downstream processing of the THP treated material, e.g. involving subsequent fermentation in one or more downstream digestion tanks.

More particularly, the prior art does not, in contrast to the present invention, describe

10 pulpers particularly suited for homogenizing and pre-heating non-Newtonian biomass material having a dry-matter content (DS%) above 8%, preferably at least 12%, and producing a material having a temperature within certain predetermined limits for subsequent thermal hydrolysis in a downstream thermal hydrolysis reactor, which are characterized in that both the total volume of the pulper and the specific placement of

15 the outlet nozzle of the pulper, i.e. for discharging the pre-heated material from the pulper, are based on the average filling volume of the downstream thermal hydrolysis reactor of the THP system.

Likewise, the prior art does, in contrast to the present invention, not describe methods,

20 systems, process equipment and plants involving THP in which:

- the average feed of non-Newtonian biomass material pr. unit of time through pulper feed lines and pulpers,
 - the average feed of pre-heated biomass material pr. unit of time through a thermal hydrolysis system, and/or
 - 25 - the average feed of hydrolyzed biomass material pr. unit of time through feed lines for subsequent processing,
- is systematically controlled based on:
- continuously or semi-continuously determining the apparent viscosity, e.g. the static yield stress, τ_o , and/or dynamic yield stress, τ_y , of the non-Newtonian biomass
 - 30 material, the pre-heated biomass material and/or the hydrolyzed biomass material, and
 - continuously or semi-continuously measuring one or more parameters of the subsequent processing system.

35 The methods, systems, process equipment and plants according to the present invention meets an increasing need for optimization of energy consumption of both the THP process as such and any subsequent processing systems, particularly in case of

non-Newtonian biomass material having a dry-matter content (DS%) above 8%, preferably at least 12%.

In addition, the methods, systems, process equipment and plants according to the present invention allows for an optimization of also any subsequent (i.e. downstream of the THP) processing steps, again particularly in case of non-Newtonian biomass material having a dry-matter content (DS%) above 8%, preferably at least 12%, preferably at least 16%, more preferably at least 18%.

10 SUMMARY OF THE INVENTION

As set out above, the prior art does not describe pulpers particularly suited for homogenizing and pre-heating non-Newtonian biomass material having a dry-matter content (DS%) above 8%, preferably at least 12%, preferably at least 16%, more preferably at least 18%, and producing a material having a temperature within certain predetermined limits for subsequent thermal hydrolysis in a downstream thermal hydrolysis reactor, which are characterized in that both the total volume of the pulper and the specific placement of the outlet nozzle of the pulper, i.e. for discharging the pre-heated material from the pulper, are based on the average filling volume of the downstream thermal hydrolysis reactor.

In contrast hereto, a preferred embodiment of a pulper according to the present invention, is characterized in that:

- the total volume of this pulper is based on the average filling volume of the downstream thermal hydrolysis reactor of the relevant THP system
- the pulper comprises an outlet nozzle, for discharging the pre-heated material from the pulper, which is placed in such a way that:
 - the part of the total volume of the pulper, which is below the outlet nozzle is a certain number of times the average filling volume of the downstream thermal hydrolysis reactor of the relevant THP system, and
 - the part of the total volume of the pulper, which is not below the outlet nozzle is a certain other factor times the average filling volume of the thermal hydrolysis reactor of the relevant THP system.

By virtue of these specific features, i.e. that both the total volume of the pulper and the specific placement of the outlet nozzle of the pulper are based on the filling volume of the downstream thermal hydrolysis reactor of the THP system, this preferred

embodiment of a pulper according to the present invention, provides the possibility to effectively control and stably maintain relevant characteristics, including not least the temperature, of preheated biomass material discharged from the pulper through the nozzle. Particularly in case of pre-heated biomass based on non-Newtonian biomass material having a dry-matter content (DS%) above 8%, preferably at least 12%, preferably at least 16%, more preferably at least 18%, this preferred embodiment of a pulper according to the present invention, thereby provides the possibility of ensuring that preheated biomass material subsequently fed to any downstream thermal hydrolysis reactor of a THP system, and/or subsequently from the THP system to any subsequent processing steps, is of a uniform character in accordance with any predetermined desirable characteristics, e.g. a certain predetermined temperature. In particular the features of the present invention ensures that pre-heated biomass material produced in a pulper from a non-Newtonian biomass material and to be subsequently fed to any downstream thermal hydrolysis reactor of a THP system, and/or subsequently from the THP system to any subsequent processing steps, is of a uniform temperature, i.e. such that the average standard variation in temperature is $<12^{\circ}\text{C}$ or more preferably $<6^{\circ}\text{C}$, and even more preferably $<2^{\circ}\text{C}$, when this standard variation in temperature is calculated based on a temperature measurement resolution of < 5 seconds, and used to calculate an overall average for each individual reactor filling.

Furthermore, none of the THP systems known from the prior art make systematic use of the relationship between the temperature and the apparent viscosity, e.g. the static yield stress, τ_0 , and/or dynamic yield stress, τ_y , of non-Newtonian biomass material being processed at the various stages of a THP process, and the importance thereof in relation to optimizing the flow of non-Newtonian biomass material having a relatively high dry-matter content (DS%), such as above 8%, preferably at least 12%, preferably at least 16%, more preferably at least 18%, through a THP process with regards to ensuring both a more efficient THP process as such, but also more efficient downstream processing of the THP treated material, e.g. involving subsequent fermentation in one or more downstream digestion tanks.

In contrast hereto, the methods, systems, process equipment and plants according to the present invention, rely on measurements establishing, which average feed; - of non-Newtonian biomass material, displaying a certain apparent viscosity, e.g. static yield stress, τ_0 , and/or dynamic yield stress, τ_y , pr. unit of time through pulper feed lines and pulpers;

- of pre-heated biomass material, displaying a certain apparent viscosity, e.g. static yield stress, τ_o , and/or dynamic yield stress, τ_y , pr. unit of time through thermal hydrolysis feed lines and thermal hydrolysis systems; and/or
 - of hydrolyzed biomass material, displaying a certain apparent viscosity, e.g. static yield stress, τ_o , and/or dynamic yield stress, τ_y , pr. unit of time through feed lines for subsequent processing systems, is, in relation to a given system for subsequent processing of THP treated material, characteristic of one or more parameters of the relevant subsequent processing steps.
- 10 The methods, systems, process equipment and plants according to the present invention, thereby, particularly in case of non-Newtonian biomass material having a dry-matter content (DS%) above 8%, preferably at least 12%, preferably at least 16%, more preferably at least 18%, provides the possibility of controlling relevant parameters of both the THP system and subsequent processing steps, by controlling
- 15 the feed of raw biomass, pre-heated biomass and/or hydrolysed biomass material displaying a certain apparent viscosity, e.g. static yield stress, τ_o , and/or dynamic yield stress, τ_y , pr. unit of time through the THP system.

This, again particularly in case of non-Newtonian biomass material having a dry-matter content (DS%) above 8%, preferably at least 12%, preferably at least 16%, more preferably at least 18%, first of all allows for optimization of the THP per se, in terms of controlling the apparent viscosity, e.g. static yield stress, τ_o , and/or dynamic yield stress, τ_y , to be displayed by the biomass material before and after undergoing the different steps of the THP in combination with a certain average feed of material per pr. Unit of time, in order to optimize e.g. the overall energy consumption of the THP vis-à-vis the characteristics of the biomass material that is to be treated.

It, however, also, again particularly in case of non-Newtonian biomass material having a dry-matter content (DS%) above 8%, preferably at least 12%, preferably at least 16%, more preferably at least 18%, allows for the optimization of any subsequent processing steps, in terms of controlling the apparent viscosity, e.g. static yield stress, τ_o , and/or dynamic yield stress, τ_y , to be displayed by a given hydrolyzed biomass material produced in a THP per unit of time, in order to optimize e.g. the yield or overall energy consumption of any subsequent processing steps in which this hydrolyzed biomass material is to be further processed.

As noted above, the methods, systems, process equipment and plants according to the present invention meets both an increasing need for optimization of energy consumption by achieving a lower overall energy consumption of both the THP process as such and any subsequent processing systems compared to the processes of the prior art, particularly in case of non-Newtonian biomass material having a dry-matter content (DS%) above 8%, preferably at least 12%, preferably at least 16%, more preferably at least 18%.

In addition the methods, systems, process equipment and plants according to the present invention allows for an optimization of also other parameters, e.g. yield, of any subsequent (i.e. downstream of the THP) processing steps, again particularly in case of non-Newtonian biomass material having a dry-matter content (DS%) above 8%, preferably at least 12%, preferably at least 16%, more preferably at least 18%.

It is therefore an objective of the present invention to provide methods, systems, process equipment and plants that ensures that pre-heated biomass material produced in a pulper from a non-Newtonian biomass material and to be subsequently fed to any downstream thermal hydrolysis reactor of a THP system, and/or subsequently from the THP system to any subsequent processing steps, is of a uniform character in accordance with any predetermined desirable characteristics, e.g. a certain predetermined temperature. In particular it is an object of the present invention to provide methods, systems, process equipment and plants that ensures that pre-heated biomass material produced in a pulper from a non-Newtonian biomass material and to be subsequently fed to any downstream thermal hydrolysis reactor of a THP system, and/or subsequently from the THP system to any subsequent processing steps, is of a uniform temperature, i.e. such that the average standard variation in temperature is $<12^{\circ}\text{C}$ or more preferably $<6^{\circ}\text{C}$, and even more preferably $<2^{\circ}\text{C}$, when this standard variation in temperature is calculated based on a temperature measurement resolution of < 5 seconds, and used to calculate an overall average for each individual reactor filling.

It is another objective of the present invention to provide methods, systems, process equipment and plants for the handling of non-Newtonian biomass material, which, in the context of processes involving THP, enables optimization of energy consumption compared to the processes of the prior art.

It is yet another object of the present invention to provide methods, systems, process equipment and plants that, in the context of processes involving THP of non-Newtonian biomass material, enables optimization of also other parameters, e.g. yield, of any subsequent (i.e. downstream of the THP) processing steps, compared to the processes of the prior art, and which are simple and easy to integrate into existing plants making use of THP by retrofitting.

These and other objectives are solved by the present invention.

- Accordingly, in a first aspect of the present invention, there is provided a system for processing a biomass material having a dry-matter content (DS%) above 8%, preferably at least 12%, such as above 14%, such as above 16%, preferably above 18%, said system comprising:
- a pulper for homogenizing and pre-heating said biomass material, and
 - a thermal hydrolysis reactor,
- said system being characterized in that:
- the total volume of said pulper is > 2.6 times and < 20 times, preferably 2.6 to 6 times, the average filling volume of said thermal hydrolysis reactor,
 - said pulper comprises an outlet nozzle, for discharging said pre-heated material from said pulper, which is placed in such a way that:
 - the part of the total volume of said pulper below said outlet nozzle is ≥ 1.6 times the average filling volume of said thermal hydrolysis reactor, and
 - the part of the total volume of said pulper not below the outlet nozzle is > 1 times the average filling volume of the thermal hydrolysis reactor.
- In some embodiments of this first aspect of the present invention, said system is further characterized in that:
- the total volume of said pulper is > 3 times the average filling volume of said thermal hydrolysis reactor,
 - the part of the total volume of said pulper below said outlet nozzle is ≥ 1.6 times the average filling volume of said thermal hydrolysis reactor, and
 - the part of the total volume of said pulper not below the outlet nozzle is > 1.4 times the average filling volume of the thermal hydrolysis reactor.
- In some embodiments of this first aspect of the present invention, said system is further characterized in that:

- the total volume of said pulper is > 3.2 times the average filling volume of said thermal hydrolysis reactor,
- the part of the total volume of said pulper below said outlet nozzle is ≥ 1.6 times the average filling volume of said thermal hydrolysis reactor, and
- 5 - the part of the total volume of said pulper not below the outlet nozzle is > 1.6 times the average filling volume of the thermal hydrolysis reactor.

In some embodiments of this first aspect of the present invention, said system is further characterized in that:

- 10 - the total volume of said pulper is > 3.4 times the average filling volume of said thermal hydrolysis reactor,
- the part of the total volume of said pulper below said outlet nozzle is ≥ 1.6 times the average filling volume of said thermal hydrolysis reactor, and
- the part of the total volume of said pulper not below the outlet nozzle is > 1.8 times
- 15 the average filling volume of the thermal hydrolysis reactor.

In an embodiment of this first aspect of the present invention, said system is further characterized in that said pre-heating in said pulper is at least partly achieved by injection of flash steam from a thermal hydrolysis system.

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In a further embodiment of this first aspect of the present invention, said system is further characterized in that:

- the part of the total volume of said pulper below said outlet nozzle, and
- the part of the total volume of said pulper not below the outlet nozzle,
- 25 are provided in the form of at least two separate interconnected chambers or tanks.

- In a further embodiment of this first aspect of the present invention, said system is further characterized in that said outlet nozzle is in the form of an overflow edge, knife or similar outlet fitted on the first of said at least two separate interconnected
- 30 chambers or tanks, which ensures that a volume corresponding to ≥ 1.6 the average filling volume of said thermal hydrolysis reactor is continuously present below said edge, knife or similar outlet in said first of said at least two separate interconnected chambers or tanks.

- 35 In a further embodiment of this first aspect of the present invention, said system is further characterized in that said pulper includes a biomass material distributor,

preferably designed as an extruder, acting to split incoming cold biomass material into smaller segments before the biomass material enters the pulper.

In a further embodiment of this first aspect of the present invention, said system is
5 further characterized in that said pulper includes a recirculation loop for recycling preheated biomass material from said pulper and mixing said preheated biomass material with cold biomass material prior to its entry into or inside said biomass material distributor.

10 In a further embodiment of this first aspect of the present invention, said system is further characterized in that the recirculation loop is capable of recycling an amount of preheated biomass material from the pulper equivalent to at least 0.5 times the amount of cold biomass material feed, preferable more than 1 times the cold biomass material feed, and even more preferably more than 2 times the cold biomass material
15 feed.

In a further embodiment of this first aspect of the present invention, said system is further characterized in that said biomass material distributor is located in the head space of the pulper above liquid level, the upper (half) section of the total volume or
20 the bottom section of the total volume of the pulper.

In a second aspect of the present invention, there is provided a method for treating a non-Newtonian biomass material having:

- a dry-matter content (DS%) of at least 8%, preferably at least 12%, such as at least
25 14%, such as at least 16%, preferably at least 18%,
 - a ratio between the chemical oxygen demand (COD) and volatile solids content (VS), COD/VS-ratio, of less than 2.0, preferably less than 1.8, and even more preferably less than 1.6, and
 - a static yield stress, τ_o , of between 150 and 2500 Pa and/or dynamic yield stress, τ_y ,
30 of between 50 and 500,
- said method comprising the steps of:

- a) feeding said non-Newtonian biomass material to one or more pulpers
by one or more pulper feed lines at a controlled DS% and/or COD
35 loading rate,

- b) homogenizing and pre-heating said non-Newtonian biomass material in said one or more pulpers resulting in a pre-heated biomass material,
- 5 c) discharging said pre-heated biomass material from said one or more pulpers,
- d) feeding said pre-heated biomass material to a thermal hydrolysis system, operated at a higher temperature than the temperature of said pre-heated biomass material, by one or more feed lines at a controlled DS% and/or COD loading rate,
- 10 e) thermally hydrolyzing said pre-heated biomass material in said thermal hydrolysis system resulting in a hydrolyzed biomass material, and subsequently processing parts of, or all of, said hydrolyzed biomass material by,
- 15 f) subsequently processing at least part of said hydrolysed biomass material in one or more subsequent processing systems by transferring said hydrolysed biomass material to said one or more subsequent processing systems, by one or more feed lines at a controlled DS% and/or COD loading rate,
- 20 wherein said method is further characterized in that:
- said controlled DS% and/or COD loading rate of said non-Newtonian biomass material through said one or more pulper feed lines and pulpers of steps a) - c), and/or
 - 25 - said controlled DS% and/or COD loading rate of said pre-heated biomass material through said one or more thermal hydrolysis system feed lines and said thermal hydrolysis system of steps d) and e), and/or
 - said controlled DS% and/or COD loading rate of said hydrolysed biomass material through said one or more feed lines of step f),
 - 30 is controlled based on:
 - continuously or semi-continuously determining the static yield stress, τ_o , and/or dynamic yield stress, τ_y , of said non-Newtonian biomass material, said pre-heated biomass material and/or said hydrolysed biomass material, by continuously or semi-continuously measuring pressure drop,
 - 35 temperature and flowrate in:

- said feed line(s) for said one or more pulpers of step a), and/or
 - said feed line(s) for said thermal hydrolysis system of step d), and/or
 - 5 - said feed line(s) for said one or more subsequent processing system of steps f), and/or
 - one or more thermal hydrolysis discharge or recirculation lines of said thermal hydrolysis system of step d) and e), and/or
 - 10 - one or more circulation lines of said one or more pulpers of steps a) – c),
- and
- continuously or semi-continuously measuring one or more parameters of said one or more subsequent processing systems of step f)
 - 15 thereby establishing, which controlled DS% and/or COD loading rate;
 - of said non-Newtonian biomass material, at said determined static yield stress, τ_o , and/or dynamic yield stress, τ_y , through said one or more pulper feed lines and pulpers of step a); and/or
 - of said pre-heated biomass material, at said determined static yield
 - 20 stress, τ_o , and/or dynamic yield stress, τ_y , through said thermal hydrolysis feed lines and thermal hydrolysis system of step d); and/or
 - of said hydrolysed biomass material, at said determined static yield stress, τ_o , and/or dynamic yield stress, τ_y , through said feed lines for said one or more subsequent processing system of step f)
 - 25 is characteristic of at least one of said one or more of parameters of said subsequent processing systems of step f).

In specific embodiments of this second aspect of the invention, said method may be further characterized in that said subsequent processing at least part of said

30 hydrolysed biomass material in one or more subsequent processing systems by transferring said hydrolysed biomass material to said one or more subsequent processing systems, by one or more feed lines at a controlled DS% and/or COD loading rate in accordance with step f) comprises:

- f1) transferring said hydrolyzed biomass material, by one or more feed
- 35 lines, to a separation step to produce at least two fractions, of which one is rich in liquid compared to said hydrolyzed biomass material and one is rich in solids compared to said hydrolyzed biomass material,

and/or,

5 f2) transferring, by one or more feed lines, said hydrolyzed biomass material, parts of, or all of, one or all of said at least two fractions produced in said separation step of step f1) to one or more processing units for anaerobic fermentation, and/or,

10 f3) transferring, by one or more feed lines, said hydrolyzed biomass material, parts of, or all of, one or all of said at least two fractions produced in said separation step of step f1) to one or more processing units for thermal reduction of organic compounds, wherein said thermal reduction is achieved by;

- 15 1) Incineration (co-incineration or mono-incineration)
2) Gasification
3) Pyrolysis or Torrefaction
4) Supercritical water oxidation
5) Supercritical water liquification
6) Hydrothermal carbonization,
20 7) Hydrothermal oxidation, and/or
8) Hydrothermal liquifaction

and/or

25 f4) transferring, by one or more feed lines, said hydrolyzed biomass material, parts of, or all of, one or all of said at least two fractions produced in said separation step of step f1) to one or more processing units for;

- 30 1) electrochemical processing, and/or
2) biological processing for reduction of organic compounds (e.g. annamox processes or other similar biological processes), and/or
3) biological processing for reduction of nutrients concentration (e.g. annamox processes), and/or
4) chemical processing for reduction of nutrients
35 concentration (e.g. evaporation or chemical stripper), and/or
5) thermal processing for reduction of nutrient concentration (e.g. steam stripper), and/or

6) chemical or thermal reaction or extraction of inorganic or organic chemical compounds in the hydrolyzed biomass material (such as magnesium-ammonium-phosphate, lignocellulosic compounds, feed additives, medical additives, cosmetic additives, etc.),

wherein said method is further characterized in that:

- said controlled DS% and/or COD loading rate of said biomass material pr. unit of time through said one or more pulper feed lines and pulpers of steps a) - c), and/or
- said controlled DS% and/or COD loading rate of said pre-heated biomass material pr. unit of time through said one or more thermal hydrolysis system feed lines and said thermal hydrolysis system of steps d) and e), and/or
- said controlled DS% and/or COD loading rate of said hydrolyzed biomass material pr. unit of time through said one or more feed lines of steps f1)-f4),

is controlled based on:

- continuously or semi-continuously determining the apparent viscosity, e.g. static yield stress, τ_0 , and/or dynamic yield stress, τ_y , of said non-Newtonian biomass material, said pre-heated biomass material and/or said hydrolyzed biomass material, by continuously or semi-continuously measuring pressure drop, temperature and flowrate in:
 - said feed lines for said one or more pulpers of step a), and/or
 - said feed lines for said thermal hydrolysis system of step d), and/or
 - said feed lines for said one or more subsequent processing system of steps f1)- f4), and/or
 - one or more thermal hydrolysis discharge or recirculation lines of said thermal hydrolysis system of step d) and e), and/or
 - one or more circulation lines of said one or more pulpers of steps a) – c),

and

5 - continuously or semi-continuously measuring at least one or more of
the following parameters of said one or more subsequent processing
systems of steps f1) - f4):

- pH
- CH₄ concentration
- amount of biogas produced pr. unit of time
- 10 - DS%,
- VS%,
- FOS/TAC ratio by the Nordmann method,
- temperature
- oxygen concentration
- 15 - CO₂ concentration
- conductivity
- salt concentration
- amount of dissolved carbon
- amount of dissolved nitrogen
- 20 - amount of suspended solids, and/or
- particle shape/size distribution

thereby establishing, which controlled DS% and/or COD loading rate;

- 25 - of said non-Newtonian biomass material, at said determined apparent
viscosity, e.g. said determined static yield stress, τ_o , and/or dynamic yield
stress, τ_y , pr. Unit of time through said one or more pulper feed lines and
pulpers of step a); and/or
- 30 - of said pre-heated biomass material, at said determined apparent
viscosity, e.g. said determined static yield stress, τ_o , and/or dynamic yield
stress, τ_y , pr. unit of time through said thermal hydrolysis feed lines and
thermal hydrolysis system of step d); and/or
- 35 - of said hydrolyzed biomass material, at said determined apparent
viscosity, e.g. said determined static yield stress, τ_o , and/or dynamic yield
stress, τ_y , pr. unit of time through said feed lines for said one or more
subsequent processing system of steps f1)- f4)

is characteristic of at least one or more of the following parameters of said pre-heated biomass material, said hydrolyzed biomass material and/or one or more subsequent processing steps of steps f1) – f4):

- 5
 - the pH,
 - the CH₄ concentration,
 - the amount of Biogas produced pr. unit of time
 - the DS%,
 - the VS%,
 - the FOS/TAC ratio as measured by the Nordmann method.
- 10
 - the temperature
 - the oxygen concentration
 - the CO₂ concentration
 - the conductivity
 - the salt concentration
- 15
 - the amount of dissolved carbon
 - the amount of dissolved nitrogen
 - the amount of suspended solids, and/or
 - the particle shape/size distribution.
- 20 In an embodiment of this second aspect of the invention, said method is further characterized in that said non-Newtonian biomass material displays an apparent viscosity at different shear rates characteristic of a static yield stress, τ_0 , of between 150 and 2500 Pa, such as above 200, such as above 250 Pa, such as above 300 Pa, such as above 350 Pa, such as above 400 Pa, such as above 450 Pa, such as above
- 25 500 Pa, such as below 2400 Pa, such as below 2300 Pa, such as below 2200 Pa, such as below 2100 Pa, such as below 2000 Pa, such as below 1900 Pa, such as below 1800 Pa, such as below 1700 Pa, such as below 1600 Pa, such as between 300 and 1700 Pa, such as between 400 and 1700 Pa, such as between 500 and 1700 Pa, such as between 600 and 1700 Pa, such as between 700 and 1700 Pa, such as
- 30 between 800 and 1700 Pa, such as between 900 and 1700 Pa, such as between 1000 and 1700 Pa and/or displays a static yield stress, τ_0 , of between 150 and 2500 Pa, such as above 200, such as above 250 Pa, such as above 300 Pa, such as above 350 Pa, such as above 400 Pa, such as above 450 Pa, such as above 500 Pa, such as below 2400 Pa, such as below 2300 Pa, such as below 2200 Pa, such as below 2100
- 35 Pa, such as below 2000 Pa, such as below 1900 Pa, such as below 1800 Pa, such as below 1700 Pa, such as below 1600 Pa, such as between 300 and 1700 Pa, such as between 400 and 1700 Pa, such as between 500 and 1700 Pa, such as between 600

and 1700 Pa, such as between 700 and 1700 Pa, such as between 800 and 1700 Pa, such as between 900 and 1700 Pa, such as between 1000 and 1700 Pa.

- In an embodiment of this second aspect of the invention, said method is further
- 5 characterized in that said non-Newtonian biomass material displays an apparent viscosity at different shear rates characteristic of a static yield stress, τ_o , of at least 500 Pa, such as at least 600 Pa, such as at least 700 Pa, such as at least 800 Pa, such as at least 900 Pa, such as at least 1000 Pa, such as at least 1100 Pa, such as at least 1200 Pa, such as at least 1300 Pa, such as at least 1400 Pa, such as at least 1500 Pa
- 10 and/or displays a static yield stress, τ_o , which is at least 500 Pa, such as at least 600 Pa, such as at least 700 Pa, such as at least 800 Pa, such as at least 900 Pa, such as at least 1000 Pa, such as at least 1100 Pa, such as at least 1200 Pa, such as at least 1300 Pa, such as at least 1400 Pa, such as at least 1500 Pa.
- 15 In an embodiment of this second aspect of the invention, said method is further characterized in that said non-Newtonian biomass material displays an apparent viscosity at different shear rates characteristic of a dynamic yield stress, τ_y , of between 50 and 500 Pa, such as above 60 Pa, such as above 70 Pa, such as above 80 Pa, such as above 90 Pa, such as above 100, such as above 150 Pa, such as above 200
- 20 Pa, such as as below 450 Pa, such as below 400 Pa, such as below 350 Pa, such as below 300 Pa, such as below 250 Pa, such as between 60 and 400 Pa, such as between 70 and 300 Pa, such as between 80 and 250 Pa and/or displays a dynamic yield stress, τ_y , of between 50 and 500 Pa, such as above 60 Pa, such as above 70 Pa, such as above 80 Pa, such as above 90 Pa, such as above 100, such as above
- 25 150 Pa, such as above 200 Pa, such as as below 450 Pa, such as below 400 Pa, such as below 350 Pa, such as below 300 Pa, such as below 250 Pa, such as between 60 and 400 Pa, such as between 70 and 300 Pa, such as between 80 and 250 Pa.

- In an embodiment of this second aspect of the invention, said method is further
- 30 characterized in that said non-Newtonian biomass material displays an apparent viscosity at different shear rates characteristic of a dynamic yield stress, τ_y , which is at least 50 Pa, such as at least 60 Pa, such as at least 70 Pa, such as at least 80 Pa, such as at least 90 Pa, such as at least 100 Pa, such as at least 110 Pa, such as at least 120 Pa, such as at least 130 Pa, such as at least 140 Pa, such as at least 150
- 35 Pa, and/or displays a dynamic yield stress, τ_y , of at least 50 Pa, such as at least 60 Pa, such as at least 70 Pa, such as at least 80 Pa, such as at least 90 Pa, such as at least

100 Pa, such as at least 110 Pa, such as at least 120 Pa, such as at least 130 Pa, such as at least 140 Pa, such as at least 150 Pa.

In an embodiment of this second aspect of the invention, said method is further
5 characterized in that said thermal hydrolysis system of steps d) and e) includes:
- one or more reactors working in parallel or series in which said pre-heated biomass is subjected to heating and elevated pressures, and
- one or more flashtanks to which said biomass is transferred from said one or more reactors, whereby a pressure reduction occurs in one or more stages wherefrom flash
10 steam results,
and that:
- said pre-heating of said biomass material in said one or more pulpers of steps a) - c), which may work in parallel or series, is achieved by injection of flash steam recovered from said thermal hydrolysis system of steps d) and e).

15 In further embodiments of this second aspect of the invention, said method is further characterized in that said non-Newtonian biomass material has a dry-matter content (DS%) above 20% and:
- at least 50% of said resulting hydrolyzed biomass material is recirculated by transport
20 from i) downstream said hydrolysis system of steps d) and e), to ii) upstream said hydrolysis system of steps d) and e), and/or
- the biomass material is pre-heated in said pulpers of steps a) to c) and thermally hydrolysed in said thermal hydrolysis system of steps d) and e) by subjecting said biomass material to multiple steps involving stepwise heating and cooling.

25 In further embodiments of this second aspect of the invention, said method is further characterized in that said non-Newtonian biomass material has a dry-matter content (DS%) above 20% and wherein said one or more subsequent processing systems of step f) includes:

30 f1) a separation step to produce at least two fractions, of which one is rich in liquid compared to said hydrolysed biomass material and one is rich in solids compared to said hydrolysed biomass material,
and,
f2) transferring, by one or more feed lines, said hydrolysed biomass
35 material, parts of, or all of, one or all of said at least two fractions produced in said separation step of step f1) to one or more processing units for anaerobic fermentation,

and,

f3) transferring, by one or more feed lines, said hydrolysed biomass material, parts of, or all of, one or all of said at least two fractions produced in said separation step of step f1) to one or more processing units for thermal reduction of organic compounds,

and wherein:

- at least part of a material resulting from said anaerobic fermentation of step f2) is at least partly dewatered and the resulting dewatered material is transferred by one or more feed lines, to said one or more processing units for thermal reduction of organic compounds of step f3).

In embodiments of this second aspect of the invention, in which the biomass material is pre-heated in said pulpers of steps a) to c) and thermally hydrolysed in said thermal hydrolysis system of steps d) and e) by subjecting said biomass material to multiple steps involving stepwise heating and cooling, this stepwise heating and cooling will preferably take place in one or more pulpers for heating, one or more reactors for treatment at a pre-selected temperature of above 150°C, more preferably above 160°C, or even more preferably above 180°C, and one or more flashtanks for pressure reduction and/or cooling. The individual vessels employed in this stepwise heating and cooling may be connected in parallel or in series.

Any of the above embodiments, in which the biomass material is pre-heated in said pulpers of steps a) to c) and thermally hydrolysed in said thermal hydrolysis system of steps d) and e) by subjecting said biomass material to multiple steps involving stepwise heating and cooling, could be performed either as a continuous or a discontinuous process with tubular or tank vessels.

In the above embodiments, in which the biomass material is pre-heated in said pulpers of steps a) to c) and thermally hydrolysed in said thermal hydrolysis system of steps d) and e) by subjecting said biomass material to multiple steps involving stepwise heating and cooling, the total volume of each preheating pulper is typically equal to or greater than the corresponding average reactor filling volume. More preferably the total volume of each preheating pulper is typically equal to or greater than 2 times the corresponding average reactor filling volume. In particularly preferred embodiments, in which the biomass material is pre-heated in said pulpers of steps a) to c) and thermally hydrolysed in said thermal hydrolysis system of steps d) and e) by subjecting said biomass material to multiple steps involving stepwise heating and cooling, the

preheating pulper used is a pulper in accordance with the first aspect of the present invention.

In a further embodiment of this second aspect of the invention, said method is further
5 characterized in that said resulting hydrolyzed biomass material of step e) is
recirculated by transport from i) downstream said hydrolysis system of steps d) and e),
to ii) upstream one or more of said pulpers of steps a) - c) and mixed with said non-
Newtonian biomass material thereby acting to reduce the apparent viscosity, e.g. static
yield stress, τ_o , and/or dynamic yield stress, τ_y , of the material fed to said pulpers.

10

In yet a further embodiment of this second aspect of the invention, said method is
further characterized in that preheated biomass material from one or more pulpers of
steps a) – c) is recirculated by transport to upstream said one or more pulpers of steps
a) – c) and mixed with said non-Newtonian biomass material thereby acting to reduce
15 the apparent viscosity, e.g. static yield stress, τ_o , and/or dynamic yield stress, τ_y , of the
material fed to said pulpers.

In yet a further embodiment of this second aspect of the invention, said method is
further characterized in that recirculating said resulting hydrolyzed biomass of step e)
20 or preheated biomass material of step b) is achieved by use of one or more mixing
augers and pumps, preferably progressive cavity pumps, and preferably one or more
augers with a conveying capacity of at least 1.5 times that of the pumps.

In yet a further embodiment of this second aspect of the invention, said method is
25 further characterized in that recirculating said resulting hydrolyzed biomass or
preheated biomass material is achieved by use of one or more mixing augers and
pumps, preferably a progressive cavity pumps, and preferably one or more augers
with a conveying capacity of at least 1.5 times that of the pumps.

30 In yet a further embodiment of this second aspect of the invention, said method further
comprises the steps of:

- adding dilution liquid, e.g. water, to reduce the apparent viscosity, e.g. the static yield
stress, τ_o , and/or dynamic yield stress, τ_y , of said non-Newtonian biomass material,
said preheated biomass material, said hydrolyzed biomass material and/or
- 35 - adding additives to said non-Newtonian biomass material acting to reduce the
apparent viscosity, e.g. the static yield stress, τ_o , and/or dynamic yield stress, τ_y , of the
material fed to said pulpers, and/or

- adding additives to said non-Newtonian biomass material acting to start an exotherm reaction that increases the temperature of said non-Newtonian biomass material, and/or
- adding additives to said non-Newtonian biomass material acting to directly or
- 5 indirectly influence other properties of the biomass material, e.g. chemical or biochemical composition, microbial composition or content, cellular structure, particle size distribution or particle shape distribution, known to directly or indirectly influence the apparent viscosity, e.g. static yield stress and/or dynamic yield stress, of said non-Newtonian biomass material.

10

In yet a further embodiment of this second aspect of the invention, said method is further characterized in that heat-exchangers are employed to recover heat from the cooling of said hydrolyzed biomass material of step e) prior to said hydrolyzed biomass material being subjected to said subsequent processing in said one or more

15 processing units of steps f1) f4), preferably by cooling said hydrolyzed biomass of step e) by subjecting said hydrolyzed biomass material to heat-exchange with water in a heat-exchanger, and subsequently injecting said water into said non Newtonian biomass material of step a) or pre-heated biomass material of step b).

- 20 In yet a further embodiment of this second aspect of the invention, said method is further characterized in that said recovered heat is used to either:
- heat said non-Newtonian biomass material of step a) prior to said pre-treatment in said one or more pulpers of steps a) – c), or
 - heat said pre-heated biomass material of step b) in said thermal hydrolysis system of
 - 25 steps d) and e).

- In yet a further embodiment of this second aspect of the invention, said method is further characterized in that the apparent viscosity of said non-Newtonian biomass material of step a) is indicative of, and/or said static yield stress, τ_0 , of said non-
- 30 Newtonian biomass material of step a) is, above 2000 Pa, such as above 2200 Pa, such as above 2300 Pa, and the apparent viscosity of the material fed to said pulpers is reduced to a value indicative of a static yield stress, τ_0 , below 1700 Pa, such as below 1500 Pa, and/or the static yield stress, τ_0 , of the material fed to said pulpers is reduced to, below 1700 Pa, such as below 1500 Pa, and
- 35 - optionally inorganic particles and/or undissolved material is continuously separated from said hydrolyzed biomass material of step by degritting e) prior to said subsequent processing of steps f1) – f4).

In yet a further embodiment of this second aspect of the invention, said method is further characterized in that the apparent viscosity of said non-Newtonian biomass material of step a) is indicative of, and/or said dynamic yield stress, τ_y , of said non-Newtonian biomass material of step a) is, above 300 Pa, such as above 350 Pa, such as above 400 Pa, and the apparent viscosity of the material fed to said pulpers is reduced to a value indicative of a dynamic yield stress, τ_y , below 300 Pa, such as below 250 Pa, and/or the dynamic yield stress, τ_y , of the material fed to said pulpers is reduced to, below 300 Pa, such as below 250 Pa, and

5 - optionally inorganic particles and/or undissolved material is continuously separated from said hydrolyzed biomass material of step by degritting e) prior to said subsequent processing of steps f1) – f4).

10

In yet a further embodiment of this second aspect of the invention, said method is further characterized in that at least part of the at least one fraction of step f1) rich in liquid compared to said hydrolyzed biomass material is recirculated by transport to

15 - upstream one or more of said pulpers of steps a) - c) and mixed with said non-Newtonian biomass material thereby acting to reduce the apparent viscosity, e.g. static yield stress, τ_o , and/or dynamic yield stress, τ_y , of the material fed to said pulpers,

20 - upstream said hydrolysis system steps d) - e) and mixed with said pre-heated biomass material thereby acting to reduce the apparent viscosity, e.g. static yield stress, τ_o , and/or dynamic yield stress, τ_y , of the material fed to said hydrolysis system, and/or

- upstream said separation step f1) and mixed with said hydrolyzed biomass material thereby acting to reduce the apparent viscosity, e.g. static yield stress, τ_o , and/or dynamic yield stress, τ_y , of the material fed to said separation step f1).

25

In particularly preferred embodiments of said second aspect of the invention, the homogenization and pre-heating of said non-Newtonian biomass material in said one or more pulper(s) in steps a) – c), and the thermal hydrolysis of steps d) - e) is performed in a system in accordance with the first aspect of the present invention.

30

Any of the embodiments of the first aspect of the invention may be combined with any of the embodiments of the second aspect.

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In a third aspect of the invention, there is provided a method for retrofitting an existing plant for thermal hydrolysis of a non-Newtonian biomass material having a dry-matter

- content (DS%) of at least 8%, preferably at least 12%, such as at least 14%, such as at least 16%, preferably at least 18%, and a ratio between the chemical oxygen demand (COD) and volatile solids content (VS), COD/VS-ratio, of less than 2.0, preferably less than 1.8, and even more preferably less than 1.6, 6 and
- 5 a static yield stress, τ_0 , of between 150 and 2500 Pa and/or a dynamic yield stress, τ_y , of between 50 and 500, which non-Newtonian biomass material is to be used in an anaerobic fermentation, digestion or another process aimed at producing or extracting methane or other valuable substances, whereby said retrofitting ensures that said plant comprises at least the following:
- 10
- a) means for feeding said non-Newtonian biomass material to one or more pulpers by one or more pulper feed lines at a controlled DS% and/or COD loading rate
- 15
- b) means for homogenizing and pre-heating said non-Newtonian biomass material in said one or more pulpers resulting in a pre-heated biomass material,
- c) means for discharging said pre-heated biomass material from said one
- 20 or more pulpers,
- d) means for feeding said pre-heated biomass material to a thermal hydrolysis system, operated at a higher temperature than the temperature of said pre-heated biomass material, by one or more feed
- 25 lines at a controlled DS% and/or COD loading rate,
- e) means for thermally hydrolyzing said pre-heated biomass material in said thermal hydrolysis system resulting in a hydrolyzed biomass material, and
- 30
- f) subsequently processing at least part of said hydrolyzed biomass material in one or more subsequent processing systems by transferring said hydrolysed biomass material to said one or more subsequent processing systems, by one or more feed lines at a controlled DS%
- 35 and/or COD loading rate,

wherein said means are further characterized in that:

- said controlled DS% and/or COD loading rate of said non-Newtonian biomass material through said one or more pulper feed lines and pulpers of steps a) – c), and/or
- 5 - said controlled DS% and/or COD loading rate of said pre-heated biomass material through said one or more thermal hydrolysis system feed lines and said thermal hydrolysis system of steps d) and e), and/or
- said controlled DS% and/or COD loading rate of said hydrolysed biomass material through said one or more feed lines of step f),
- is controlled based on:
- 10 - continuously or semi-continuously determining the static yield stress, τ_o , and/or dynamic yield stress, τ_y , of said non-Newtonian biomass material, said pre-heated biomass material and/or said hydrolysed biomass material, by continuously or semi-continuously measuring pressure drop, temperature and flowrate in:
- 15 - said feed line(s) for said one or more pulpers of step a), and/or
- said feed line(s) for said thermal hydrolysis system of step d), and/or
- 20 - said feed line(s) for said one or more subsequent processing system of steps f), and/or
- one or more thermal hydrolysis discharge or recirculation lines of said thermal hydrolysis system of step d) and e), and/or
- one or more circulation lines of said one or more pulpers of steps a) – c),
- 25 and
- continuously or semi-continuously measuring one or more parameters of said one or more subsequent processing systems of step f)
- thereby establishing, which controlled DS% and/or COD loading rate;
- 30 - of said non-Newtonian biomass material, at said determined static yield stress, τ_o , and/or dynamic yield stress, τ_y , through said one or more pulper feed lines and pulpers of step a); and/or
- of said pre-heated biomass material, at said determined static yield stress, τ_o , and/or dynamic yield stress, τ_y , through said thermal hydrolysis feed lines and thermal hydrolysis system of step d); and/or
- 35

- of said hydrolysed biomass material, at said determined static yield stress, τ_o , and/or dynamic yield stress, τ_y , through said feed lines for said one or more subsequent processing system of step f)
is characteristic of at least one of said one or more of parameters of said subsequent
5 processing systems of step f).

In specific embodiments of this third aspect of the invention, said means may be further characterized in that said subsequent processing at least part of said hydrolysed biomass material in one or more subsequent processing systems by
10 transferring said hydrolysed biomass material to said one or more subsequent processing systems, by one or more feed lines at a controlled DS% and/or COD loading rate in accordance with step f) comprises:

15 f1) means for transferring said hydrolyzed biomass material, by one or more feed lines, to a separation step to produce at least two fractions, of which one is rich in liquid compared to said hydrolyzed biomass material and one is rich in solids compared to said hydrolyzed biomass material, and/or,

20 f2) means for transferring, by one or more feed lines, said hydrolyzed biomass material, parts of, or all of, one or all of said at least two fractions produced in said separation step of step f1) to one or more processing units for anaerobic fermentation, and/or,

25 f3) means for transferring, by one or more feed lines, said hydrolyzed biomass material, parts of, or all of, one or all of said at least two fractions produced in said separation step of step f1) to one or more processing units for thermal reduction of organic compounds, wherein
30 said thermal reduction is achieved by;

- 1) Incineration (co-incineration or mono-incineration)
- 2) Gasification
- 3) Pyrolysis or Torrefaction
- 4) Supercritical water oxidation
- 35 5) Supercritical water liquification
- 6) Hydrothermal carbonization,
- 7) Hydrothermal oxidation, and/or

8) Hydrothermal liquifaction

and/or

- 5 f4) means for transferring, by one or more feed lines, said hydrolyzed biomass material, parts of, or all of, one or all of said at least two fractions produced in said separation step of step f1) to one or more processing units for;
- 10 1) electrochemical processing, and/or
2) biological processing for reduction of organic compounds (e.g. annamox processes or other similar biological processes), and/or
3) biological processing for reduction of nutrients concentration (e.g. annamox processes), and/or
15 4) chemical processing for reduction of nutrients concentration (e.g. evaporation or chemical stripper),
5) thermal processing for reduction of nutrient concentration (e.g. steam stripper), and/or
6) chemical or thermal reaction or extraction of inorganic or
20 organic chemical compounds in the hydrolyzed biomass material (such as magnesium-ammonium-phosphate, lignocellulosic compounds, feed additives, medical additives, cosmetic additives, etc),

wherein said means are further characterized in that:

- 25 - said controlled DS% and/or COD loading rate of said biomass material pr. unit of time through said one or more pulper feed lines and pulpers of steps a) – c), and/or
- said controlled DS% and/or COD loading rate of said pre-heated
30 biomass material pr. unit of time through said one or more thermal hydrolysis system feed lines and said thermal hydrolysis system of steps d) and e), and/or
- said controlled DS% and/or COD loading rate of said hydrolyzed biomass material pr. unit of time through said one or more feed lines of
35 steps f1)-f4),

can be controlled based on:

- 5 - continuously or semi-continuously determining the apparent viscosity, e.g. the static yield stress, τ_o , and/or dynamic yield stress, τ_y , of said non-Newtonian biomass material, said pre-heated biomass material and/or said hydrolyzed biomass material, by continuously or semi-continuously measuring pressure drop, temperature and flowrate in:
- said feed lines for said one or more pulpers of step a), and/or
 - 10 - said feed lines for said thermal hydrolysis system of step d), and/or
 - said feed lines for said one or more subsequent processing system of steps f1)- f4), and/or
 - one or more thermal hydrolysis discharge or recirculation lines of said thermal hydrolysis system of step d) and e),
 - 15 and/or
 - one or more circulation lines of said one or more pulpers of steps a) – c),
- 20 and optionally
- continuously or semi-continuously measuring at least one or more of the following parameters of said one or more subsequent processing systems of steps f1) – f4):
- pH
 - 25 - CH₄ concentration
 - amount of biogas produced pr. Unit of time
 - DS%,
 - VS%,
 - FOS/TAC ratio by the Nordmann method,
 - 30 - temperature
 - oxygen concentration
 - CO₂ concentration
 - conductivity
 - salt concentration
 - 35 - amount of dissolved carbon
 - amount of dissolved nitrogen
 - amount of suspended solids, and/or

- particle shape/size distribution

whereby said means allow for establishing, which controlled DS% and/or COD loading rate;

5

- of said non-Newtonian biomass material, at said determined apparent viscosity, e.g. static yield stress, τ_o , and/or dynamic yield stress, τ_y , pr. unit of time through said one or more pulper feed lines and pulpers of step a);

10

- of said pre-heated biomass material, at said determined apparent viscosity, e.g. static yield stress, τ_o , and/or dynamic yield stress, τ_y , pr. unit of time through said thermal hydrolysis feed lines and thermal hydrolysis system of step d); and/or

15

- of said hydrolyzed biomass material, at said determined apparent viscosity, e.g. static yield stress, τ_o , and/or dynamic yield stress, τ_y , pr. unit of time through said feed lines for said one or more subsequent processing system of steps f1)- f4)

is characteristic of at least one or more of the following parameters of said pre-heated biomass material, said hydrolyzed biomass material and/or one or more subsequent processing steps of steps f1) – f4):

- the pH,
- the CH₄ concentration,
- the amount of Biogas produced pr. unit of time
- 25 - the DS%,
- the VS%,
- the FOS/TAC ratio as measured by the Nordmann method.
- the temperature
- the oxygen concentration
- 30 - the CO₂ concentration
- the conductivity
- the salt concentration
- the amount of dissolved carbon
- the amount of dissolved nitrogen
- 35 - the amount of suspended solids, and/or
- the particle shape/size distribution.

In an embodiment of this third aspect of the invention, said method is further characterized in that said non-Newtonian biomass material displays an apparent viscosity at different shear rates characteristic of a static yield stress, τ_o , of at least 500 Pa, such as at least 1000 Pa, such as at least 1500 Pa, and/or displays a static yield stress, τ_o , of at least 500 Pa, such as at least 1000 Pa, such as at least 1500 Pa.

In an embodiment of this third aspect of the invention, said method is further characterized in that said non-Newtonian biomass material displays an apparent viscosity at different shear rates characteristic of a dynamic yield stress, τ_y , of at least 50 Pa, such as at least 60 Pa, such as at least 70 Pa, such as at least 80 Pa, such as at least 90 Pa, such as at least 100 Pa and/or displays a dynamic yield stress, τ_y , of at least 50 Pa, such as at least 60 Pa, such as at least 70 Pa, such as at least 80 Pa, such as at least 90 Pa, such as at least 100 Pa.

Any of the embodiments of the first and second aspects of the invention may be combined with any of the embodiments of the third aspect.

In a fourth aspect of the invention, there is provided a method for retrofitting an existing system comprising a pulper for homogenizing and pre-heating a biomass material having a dry-matter content (DS%) above 8%, preferably at least 12%, such as above 14%, such as above 16%, preferably above 18%, and a thermal hydrolysis reactor for subsequent thermal hydrolysis of said biomass material, whereby said retrofitting ensures that said pulper is characterized in that:

- the total volume of said pulper is > 2.6 times and < 20 times, preferably 2.6 to 6 times, the average filling volume of said thermal hydrolysis reactor
- said pulper comprises an outlet nozzle, for discharging said pre-heated material from said pulper, which is placed in such a way that:
 - the part of the total volume of said pulper below said outlet nozzle is ≥ 1.6 times the average filling volume of said thermal hydrolysis reactor, and
 - the part of the total volume of said pulper not below the outlet nozzle is > 1 times the average filling volume of the thermal hydrolysis reactor.

In one embodiment of the fourth aspect of the invention a varying pressure drop in the pulper feed line resulting from varying dry solids concentration in the pulper feed system (and the therefrom resulting variations in apparent viscosity), and the consequential difficulty in establishing a stable dilution rate to control apparent viscosity, may be mitigated by intensifying the mixing in pulper. This intensified mixing

- may be obtained by recycling, pre-heated and/or hydrolysed material and mixing it into the pulper feed system to homogenize the characteristics of the material ultimately fed to the pulper. This will in turn improve performance of the pulper as regards producing a material having a temperature within certain predetermined limits, improve the heat
- 5 recovery rate of the overall pulper system, enable enhanced operation at elevated dry solids concentration and enable the fixing of a dilution rate based on a more stable apparent viscosity measurement in the pulper feed line. Thereby being able to feed a biomass material with a more stable apparent viscosity to the pulper makes it possible to operate stably at increased dry solids concentration as a more predictable feed
- 10 apparent viscosity will ultimately lower the magnitude of any apparent viscosity safety margin. In particular it is ensured that pre-heated biomass material produced in a pulper from a non-Newtonian biomass material and to be subsequently fed to any downstream thermal hydrolysis reactor of a THP system, and/or subsequently from the THP system to any subsequent processing steps, is of a uniform temperature, i.e.
- 15 such that the average standard variation in temperature is $<12^{\circ}\text{C}$ or more preferably $<6^{\circ}\text{C}$, and even more preferably $<2^{\circ}\text{C}$, when this standard variation in temperature is calculated based on a temperature measurement resolution of < 5 seconds, and used to calculate an overall average for each individual reactor filling.
- 20 Any of the embodiments of the first, second and third aspects of the invention may be combined with any of the embodiments of the fourth aspect.

The optimal temperature and pressures in the individual vessels in a method, system or plant according to the present invention will depend on the temperature in the feed

25 to the THP. Typically, the temperature in the feed to a THP is approximately 15°C , and the normal range is from 10 to 30°C , such as 15 - 25°C .

Flashsteam is preferably injected below liquid level in the pulpers. This ensures that steam condenses in the liquid while other non-condensable gases travel through the

30 liquid and enters the headspace. Temperature and pressure transmitters are used to calculate the partial pressure of steam and other non-condensable gases in the headspace of the pulper vessels. Input from these instruments are used to control a valve that releases gases out from the vessels. This ensures that steam carried with the process gas may be used for heating in other parts of the process.

35 Typically, the temperature of the liquid material fed to the pulper or pulpers in a method, system or plant according to the present invention will be in the range from 10

to 30 C, such as 15-25 C, e.g. 20-25 C, and the hydrolysis temperature applied in the one or more reactors working in parallel or series downstream of the pulper(s) will be in the range between 120 to 220 C, such as 140 to 180 C, such as 155-165 C, e.g. app 160 C depending on ambient temperature and feedstock.

5

The apparent viscosity of most liquid materials, and the static yield stress, τ_o , and/or dynamic yield stress, τ_y , decreases with increasing temperature and increases with increasing dry solids content. For e.g. materials such as sludge from waste water treatment plants, the apparent viscosity, and the static yield stress, τ_o , and/or dynamic yield stress, τ_y , is normally greatly reduced by heating the material from ambient temperatures to approximately at least 50 C, such as app. At least 60 C, such as app. At least 70 C. Apparent viscosity, and the static yield stress, τ_o , and/or dynamic yield stress, τ_y , continues to decrease by heating to higher temperatures, but to a somewhat smaller extent. With low temperature in the pulper(s) it can become necessary to operate the process with lower dry solids content in the feed to keep the apparent viscosity, and the static yield stress, τ_o , and/or dynamic yield stress, τ_y , at a manageable level.

Also, as the skilled person would know, it is possible to pre-heat the incoming liquid material by using hot water for dilution, heat exchangers or the like. In such situations, i.e. if both the temperature of the liquid material feed to the pulper(s) and the hydrolysis temperature applied in the one or more reactors working in parallel or series downstream of the pulper(s) is sufficiently high, the working pressure of the pulper(s) will typically be more than 1 barA. One example of this would be a process, in which the liquid material is pre-heated to a temperature of 40 C, with small amounts of non-condensable gases, and where the hydrolysis is performed at a temperature of 220 C (and 23.2 barA). In this case, the pulper(s) will typically be run at 115 C and about 1.8 barA. Another example of such a method and/or plant would be a method/plant relying on feed having a temperature of about 65-70 C and a reactor pressure about 7 barA.

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However, in the majority of situations in a method, system or plant according to the present invention the biomass material temperature and the hydrolysis temperature will be lower than 60 C and 200 C, respectively, such as lower than 40 C and 180 C, respectively.

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An important aspect of the present invention is to recover heat. It is crucial that all steam brought back to the pre-heating vessels condenses into the material that is to

be pre-heated. This becomes extra challenging in pulper(s) that operate(s) at low temperatures because apparent viscosity, and static yield stress, τ_o , and/or dynamic yield stress, τ_y , increases with decreasing temperatures. However, so-called steam 33escribe33g, which is characterized by steam traveling from the injection point
5 through the liquid surface, can be avoided by ensuring efficient mixing of the material in the pre-heating vessel. The density of steam decreases with decreasing pressure. As a result, the volume of steam transferred to a pre-heating vessel will in most scenarios be large. This effect can be exploited and used to mix the material in the pre-heating vessel by injecting steam at carefully designed injection points. This
10 makes it possible to treat highly viscous materials with high dry solids content, such as above 8%, preferably at least 12%, even at low temperatures. Efficient mixing is not only important for ensuring condensation of all steam returned to the pre-heating vessel(s), but also for homogenizing the material prior to further processing. Thus, homogenizing the material prior to treatment in any downstream reactor(s) also
15 ensures a more complete hydrolysis.

For most relevant materials, apparent viscosity, and static yield stress, τ_o , and/or dynamic yield stress, τ_y , increases with dry solid concentration, whereas apparent viscosity decreases with increasing temperatures. The apparent viscosity, and static
20 yield stress, τ_o , and/or dynamic yield stress, τ_y , of raw materials such as sludge is typically greatly reduced upon heating from ambient temperatures to about 50 C, such as about 50 C to 70 C, such as 60 to 65 C. Heating to even higher temperatures will lead to a further reduction in apparent viscosity, and static yield stress, τ_o , and/or dynamic yield stress, τ_y . The present invention enables operation at high dry solids
25 concentration. As would be known by the skilled person, high dry solids concentrations will in itself contribute to reduced steam consumption in the magnitude of app. 10%-30% depending on material characteristics.

A further preferred embodiment of the present invention is for any pulper(s) to include
30 a steam introduction system that enables high intensity mixing by using voluminous vapors, whereby the need for mechanical mixing as such would be reduced. Whichever means of mixing are used in a certain embodiment, enhanced mixing can be achieved through an optimized orientation of the lances and through additional pumping.

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The present invention, thus, provides a method for continuous or batch hydrolysis of material by using pre-heating and cooling by using injection of flash steam and facilitating steam flashing, respectively.

- 5 In yet a further preferred embodiment of a method or a plant according to the present invention the preheating pulper feed is either introduced into the bottom of the preheating pulper, or above liquid level of the preheating pulper in combination with a material size reduction and distribution system that increases specific surface area of the cold material, or below liquid level of the preheating pulper in combination with a
10 material size reduction and distribution system that increases specific surface area of the cold material.

The reactors of a method or plant according to the present invention can be in series or in parallel.

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BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1(A) shows a rotational rheometer for measuring the static and dynamic yield stress of a biomass material. The rotational rheometer includes a vane that can be immersed in a cup comprising the biomass material.

- 20 Figure 1(B) shows the viscosity characteristics, including the relation between shear rate and shear stress, of different kinds of non-Newtonian liquids/biomass materials.

Figure 1(C) shows typical shear stress-shear rate curves obtained for 2 different samples of municipal sewage sludge obtained by use of a rotational rheometer as the
25 one shown in figure 1 (A).

Figure 1(D) shows typical shear stress-shear rate curve obtained for 2 hydrolysed municipal sewage sludge obtained by use of a rotational rheometer as the one shown in figure 1 (A).

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Figure 2 shows the viscosity characteristics of different kinds of sludge as regards the relation between shear rate and shear stress.

- 35 Figure 3 illustrates the calculated pressure drop (head loss) in a pulper feed line as a function of the flow rate for a certain type of waste activated sludge as a function of

flowrate at high temperature (low pressure drop) and at low temperature (high pressure drop), respectively.

Figure 4 shows the calculated head loss (bar) as a function of pipe diameter (mm) for a sludge transfer line for two different sludge qualities and pipe configurations at approx. 20-25°C.

Figure 5 illustrates the average temperature of a sludge mixture as a function of return flow temperature.

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Figure 6 illustrates the average temperature of a sludge mixture as function of return flow ratio at a return flow temperature of 90°C and a feed flow temperature of 20°C.

Figure 7 shows a possible design of a particular beneficial pulper design of the methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention.

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Figure 8 shows embodiments of the present invention including a particular beneficial pulper design according to the present invention.

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Figure 9 shows a preferred sludge extruder in a particular beneficial pulper design according to the present invention.

Figure 10A shows data from a case study in relation to performance data of a pulper modification upgrade, involving the upgrade from a prior art design (8 hour trends) to a particular beneficial pulper design according to the present invention (16 hour trends).

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Figure 10B shows the standard deviation of reactor feed temperature for individual reactor fillings in a method according to the present invention, employing a pulper according to the present invention based on temperature measurements every 5 seconds.

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Figure 11 shows data from a case study in relation to performance data of a pulper modification upgrade as regards reactor flow, involving the upgrade from a prior art design (without new invention) to a particular beneficial pulper design according to the present invention (with new invention).

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Figures 12, 13A and 13B show the relationship between τ_o and WAS% when operating at selected dry solids content from 16% to 18%DS, during development and testing of the particularly beneficial pulper design according to the present invention described in example 4.

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Figure 14 shows the relationship between specific energy content, measured as COD/VS and rheology, measured as τ_o when making use of a particularly beneficial pulper design according to the present invention described in example 4.

- 10 Figure 15 shows the relationship between τ_o and WAS/Primary sludge ratio when making use of a particularly beneficial pulper design according to the present invention described in example 4.

- Figure 16 shows the relationship between τ_o and organic Nitrogen content of VS when making use of a particularly beneficial pulper design according to the present invention described in example 4.

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DETAILED DESCRIPTION

- 20 Below the present invention will be described in further detail with reference to certain specific embodiments, and the nomenclature also used in the accompanying figures.

- The present invention relates to methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP), which make use of pulpers for pre-heating. The present invention also relates to methods for retrofitting existing plants employing Thermal Hydrolysis Processes (THP). In particular, the present invention relates to methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP), which are useful for the processing of "biomass material", having a dry-matter content (DS%) of at least 8%, preferably at least 12%, such as at least 14%, such as at least 16%, such as at least 18%, such as at least 20%.

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- One source of "biomass material", which may be processed in the methods, systems, process equipment and plants of the present invention stems from so-called primary wastewater treatment, involving gravity sedimentation of screened, degrittled wastewater to remove settleable solids. In many scenarios, this will amount to slightly more than one-half of the suspended solids ordinarily present in wastewater. The

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residue from primary treatment is a concentrated suspension of particles in water called, also often referred to as "primary sludge" or "primary biosolid". Another source of "biomass material", which may be processed in the methods, systems, process equipment and plants of the present invention stems from so-called secondary

5 municipal wastewater treatment, e.g. accomplished by using a biological treatment process, where microorganisms in suspension, attached to media, or in ponds or other processes, are used to remove biodegradable organic material from the wastewater. Part of the organic material is oxidized by the microorganisms to produce carbon dioxide and other end products, and the remainder provides the energy and materials

10 needed to support microorganism growth. The microorganisms thereby formed settle as particles, and, following biological treatment, this excess biomass is separated in sedimentation tanks as a concentrated suspension called "secondary sludge"/ "secondary biosolid" or "waste activated sludge"/"WAS". In many wastewater treatment plants, a portion of the WAS will be returned to the secondary treatment process and

15 mixed with incoming wastewater from which primary sludge has already been removed. This part, i.e. the returned part, is sometimes referred to as "Return Activated Sludge"/"RAS". Thus, "primary sludge"/"primary biosolid", "secondary sludge"/"secondary biosolid"/"waste activated sludge"/"WAS" and "Return Activated Sludge"/"RAS" are all solid, semisolid, or slurry residual materials, which are produced

20 as a by-product of wastewater treatment processes.

Hence, in the context of the present invention the term "biomass material" is to be construed as referring to any material comprising organic material, i.e. material based on living organisms, such as microorganisms, plants and animals, which may be used

25 as a "substrate" in methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) according to the present invention. The most common "biomass materials", and hence "substrates", are energy crops, agricultural crop residues, forestry residues, algae, wood processing residues, municipal waste, and wet waste, such as crop wastes, forest residues, purpose-grown grasses, woody

30 energy crops, algae, industrial wastes, sorted municipal solid waste [MSW], urban wood waste, and food waste and waste from industry, farms and households, such as "wastewater" (see above), "biological sludge", "sludge" or the like. Unless specifically specified below terms like, "waste-water", "biological sludge", "sludge" ("primary sludge"/"primary biosolid" and "secondary sludge"/"secondary biosolid"), "waste

35 activated sludge"/"WAS" and "Return Activated Sludge"/"RAS" are as a starting point used interchangeably in the context of the present invention and are in the context of the aspects and embodiments described herein below, all to be construed to be

examples of a "biomass material", which may be used as a "substrate" in the methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention. In certain aspects and embodiments described below, it is specified that the "biomass material", i.e. "substrate", which is processed,

5 comprises one specific "biomass material" or a specific mixture of several specific "biomass materials", e.g. "wastewater", "primary sludge"/"primary biosolid", "secondary sludge"/"secondary biosolid"/"waste activated sludge"/"WAS" and/or "Return Activated Sludge"/"RAS". However, as will be evident from the below, this possible further specification of the "biomass material", is intended to provide specific examples of how

10 a skilled person may arrive at a "biomass material" characterised by e.g. a specific apparent viscosity and/or a specific static yield stress, τ_o , and/or dynamic yield stress, τ_y , a specific dry-matter content (DS%) and/or a specific ratio between the chemical oxygen demand (COD) and volatile solids content (VS), the so-called COD/VS-ratio. As will be evident to a skilled person, however, a "biomass material", i.e. "substrate",

15 displaying similar specific characteristics could equally well be obtained from another "biomass material", or another mixture of "biomass materials", than the one(s) specifically identified in the relevant aspect and/or embodiment. In the context of the present invention the term "Non-newtonian biomass material" is to be construed as referring to a biomass material (see above), which does not follow Newton's law of

20 viscosity. Hence, the viscosity of a "non-Newtonian biomass material" can change when under force to being either more liquid or more solid, and the relation between the shear stress and the shear rate, is either not linear and/or does not pass through the origin, as for Newtonian fluids, c.f. Figure 1(B). In a "Non-Newtonian biomass material" the relation between the shear stress and the shear rate is different and a

25 constant coefficient of viscosity cannot be defined.

In the context of the present invention the term "static yield point", and the term " τ_o ", is to be construed as the amount of shear stress at which an otherwise solid material begins to flow, sometimes referred to as the "static yield stress". Hence, in the context

30 of the present invention "static yield point"/"static yield stress"/" τ_o " is to be construed as a measure of the resistance of a given "biomass material" to flow, or in other words, it is to be construed as the shear stress required to start movement of a given "biomass material" in the form of a flow. Accordingly, "static yield point"/" τ_o "/"static yield stress" is a property, which can be associated with a "biomass material" according to

35 the present invention, whereby the "biomass material" does not flow unless the applied shear stress exceeds the "static yield point"/" τ_o "/"static yield stress". The SI unit for "static yield point"/"static yield stress"/" τ_o " is Pascal (Pa) or Nm^2 .

In the context of the present invention the term “dynamic yield point”, and the term “ τ_y ”, is to be construed as the amount of shear stress to maintain flow of a material, sometimes referred to as the “dynamic yield stress”. Hence, in the context of the present invention “dynamic yield point”/“dynamic yield stress”/“ τ_y ” is to be construed as the shear stress required to maintain movement of a given “biomass material” in the form of a flow. Accordingly, “dynamic yield point”/“ τ_y ”/“dynamic yield stress” is a property, which can be associated with a “biomass material” according to the present invention, whereby the “biomass material” does not keep flowing unless the applied shear stress exceeds the “dynamic yield point”/“ τ_y ”/“dynamic yield stress”. The SI unit for “dynamic yield point”/“dynamic yield stress”/“ τ_y ” is Pascal (Pa) or Nm^2 .

The static, τ_o , and dynamic, τ_y , yield stress of a “biomass material” may be determined using a rotational rheometer. The working principle is as follow. A vane is immersed in a cup comprising the “biomass material” as shown in Figure 1(A). The shaft’s angular velocity is then gradually increased, while the applied torque is measured. This, when combined with a proper calibration, yields a shear stress-shear rate curve, e.g. as the one shown in Figure 1(C).

In the results presented in Figure 1 (C), the “biomass material” labelled “1” originates from a Bio-P process and has a dry solids content of 18.2%. The “biomass material” labelled “2” has been pretreated at approx. 80°C and has a dry solid concentration of 17.5%. The measurements for both samples were made at 21°C. From a shear rate of app. 6 s^{-1} both materials show a Bingham plastic fluid behaviour, and the plastic viscosity (slope of the curve) is close to 0. The dashed line corresponds to a dynamic yield stress of 130 Pa. Hence the key difference between the two materials is the amplitude of the static yield stress: 1200 Pa vs 400 Pa. As these measurements show there is a distinct difference between a given materials dynamic, τ_y , and static, τ_o , yield stress, and both parameters contribute to characterise the overall flow properties, i.e the apparent viscosity, of the material.

In the context of the present invention “apparent viscosity” (also sometimes referred to as shear viscosity) is the shear stress applied to a fluid divided by the shear rate. “Apparent viscosity” has the SI derived unit $\text{Pa} \cdot \text{s}$ (Pascal-second), but centipoise is frequently used in practice: ($1 \text{ mPa} \cdot \text{s} = 1 \text{ cP}$). For a Newtonian fluid, the “apparent viscosity” is constant, and equals the Newtonian viscosity of the fluid. For non-Newtonian fluids, like the “biomass materials” of the present invention, the “apparent

viscosity" depends on the shear rate as illustrated in figure 1 (C). Thus, for example the "apparent viscosity" of a so-called Bingham plastic is lower when measured at a higher shear rate. Hence, multiple measurements of "apparent viscosity" at different, well-defined shear rates, can give useful information about the behaviour of a non-Newtonian fluid/material.

As mentioned above, and shown in Figure 1(A), a very common way of measuring the "yield stress", and thereby determining the "static yield stress"/" τ_o " and "dynamic yield stress", " τ_y ", is by plotting shear stress versus shear rate data obtained from conventional rheometer measurements. Such experimental data, also referred to as equilibrium flow curves, can be interpreted with or without a rheological model such as the Herschel-Bulkley model, the Bingham Plastic model, the Bingham pseudoplastic model or the Ostwald-de Waele model, cf. Figure 2, which show data for "Dewatered raw sludge" and "Hydrolysed and digested sludge", respectively...

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The apparent viscosity characteristics of the non-Newtonian biomass material, which is preferably to be treated in the methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention, is to be characterized by being indicative of a static yield stress, τ_o , of between 150 and 2500 Pa, such as at least 1000 Pa, such as at least 1100 Pa, such as at least 1200 Pa, such as at least 1300 Pa and such as at least 1400 Pa. Alternatively, the non-Newtonian biomass material, which is preferably to be treated in the methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention, is to display a static yield stress, τ_o , of at least 1000 Pa, such as at least 1100 Pa, such as at least 1200 Pa, such as at least 1300 Pa and such as at least 1400 Pa.

The apparent viscosity characteristics of the non-Newtonian biomass material, which is preferably to be treated in the methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention, is to be characterized by being indicative of a and/or dynamic yield stress, τ_y , of between 50 and 500 Pa, such as at least 60 Pa, such as at least 70 Pa, such as at least 80 Pa, such as at least 90 Pa, such as at least 100 Pa, such as at least 110 Pa, such as at least 120 Pa, such as at least 130 Pa and such as at least 140 Pa. Alternatively, the non-Newtonian biomass material, which is preferably to be treated in the methods, systems, process equipment and plants employing Thermal Hydrolysis Processes

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(THP) of the present invention, is to display a dynamic yield stress, τ_y , of at least 150 Pa, such as at least 160 Pa, such as at least 170 Pa, such as at least 180 Pa and such as at least 190 Pa.

- 5 In some embodiments of the present invention the apparent viscosity of the a non-Newtonian biomass material, which is to be treated in the methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention, is adjusted to be indicative of a static yield stress, τ_o , below 1700 Pa such as below 1500 Pa, by reducing the apparent viscosity of a biomass material, which
- 10 would otherwise be indicative of a static yield stress, τ_o , of above 2000 Pa, such as above 2200 Pa, such as above 2500 Pa, before this is feed to the pulpers of the methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention. Alternatively, the static yield stress, τ_o , of a non-Newtonian biomass material, which is to be treated in the methods, systems,
- 15 process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention, which displays a static yield stress, τ_o , of above 2000 Pa, such as above 2200 Pa, such as above 2500 Pa, may be reduced to a static yield stress, τ_o , below 1700 Pa such as below 1500 Pa.
- 20 In some embodiments of the present invention the apparent viscosity of the a non-Newtonian biomass material, which is to be treated in the methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention, is adjusted to be indicative of a dynamic yield stress, τ_y , below 300 Pa such as below 250 Pa, by reducing the apparent viscosity of a biomass material, which
- 25 would otherwise be indicative of a dynamic yield stress, τ_y , of above 300 Pa, such as above 350 Pa, such as above 400 Pa, before this is feed to the pulpers of the methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention. Alternatively, the dynamic yield stress, τ_y , of a non-Newtonian biomass material, which is to be treated in the methods, systems,
- 30 process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention, which displays and/or dynamic yield stress, τ_y , of above 250 Pa, such as above 300 Pa, such as above 350 Pa, may be reduced to a dynamic yield stress, τ_y , below 250 Pa such as below 200 Pa.
- 35 This may be done by adding dilution liquid, e.g. water, or adding additives to said non-Newtonian biomass material acting to reduce the apparent viscosity, e.g. the static yield stress, τ_o , and/or dynamic yield stress, τ_y , of the material fed to said pulpers,

and/or by adding additives to said non-Newtonian biomass material acting to start an exotherm reaction that increases the temperature of said non-Newtonian biomass material, and/or adding additives to said non-Newtonian biomass material acting to directly or indirectly influence other properties of the biomass material, e.g. chemical or biochemical composition, microbial composition or content, cellular structure, particle size distribution or particle shape distribution, known to directly or indirectly influence the apparent viscosity, e.g. the static yield stress and/or dynamic yield stress, of said non-Newtonian biomass material. In the context of the present invention the term “chemical oxygen demand (COD)” is to be construed as referring to the amount of oxygen that’s needed to oxidise the organic matter present in a quantity of a given material. It is commonly expressed in mass of oxygen consumed over volume, which in SI units is milligrams per litre (mg/L).

In the context of the present invention the term “volatile solids content (VS)” is to be construed as referring to the amount of total solids lost when these are combusted at 550° C in the presence of excess air. One unit of VS content is % by weight.

In the context of the present invention the term “ratio between the chemical oxygen demand (COD) and volatile solids content (VS), COD/VS-ratio”, also sometimes referred to as the “specific energy content”, is to be construed as referring to the COD expressed in milligrams per litre (mg/L) divided by the VS expressed in % by weight. The COD/VS-ratio of the non-Newtonian biomass material, which is to be treated in the methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention, is less than 2.0, such as less than 1.9, such as less than 1.8, such as less than 1.7 and such as less than 1.6.

In some embodiments of the present invention the relationship between specific energy content, measured as COD/VS, and apparent viscosity, e.g. static yield stress, measured as τ_0 , and/or dynamic yield stress, measured as τ_y , of the non-Newtonian biomass material, which is to be treated in the methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention, is as depicted in Figure 14, which is based on an average energy content in Primary sludge of 1,7 and an average energy content in Waste Activated sludge of 1,45. This relationship has in the context of the present invention been found to be useful to determine the energy content, i.e. COD/VS, in sludge on basis of its apparent viscosity, e.g. static yield stress and/or dynamic yield stress. I.e. for static yield stress, τ_0 , for $\tau_0 > 500 - 1000$ Pa and COD/VS $> 1,52$ depending on type of substrate. Based on

this relationship, the COD/VS-ratio of the non-Newtonian biomass material, which is to be treated in the methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention, is preferably more than 1.5. Variations in energy content will, however, depend on sludge origin, sludge age, etc,
5 and a calibration is recommended for each sludge mix.

In the context of the present invention the term “degritting” is to be construed as referring to any process resulting in the removal of fine solid particles (grit) from a liquid carrier, e.g. by gravity separation (settling) or centrifugation.

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In the context of the present invention the term “separation” is to be construed as referring to any process resulting in the separation of a starting mixture (e.g. a hydrolysed biomass material) into different portions and/or fractions thereof through differences in physical and/or chemical properties.

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In the context of the present invention the term “anaerobic fermentation” is to be construed as referring to any process that results in the conversion of a hydrolysed biomass material to a desirable end product (e.g. organic acids, gases or alcohols), under anaerobic conditions.

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In the context of the present invention the term “Incineration” is to be construed as referring to full combustion of a given material, e.g. a hydrolysed biomass material, with excess of air. Incineration may prevent spreading of diseases and environmentally hazardous substances including micro plastics. Incineration is a
25 method that eliminates the concerns of recycling biosolids to agricultural land and other land applications. Incineration may also be used to eliminate the need for recovery and reuse of a range of micro and macro nutrients. Incineration is a common technology to eliminate toxic substances. According to the European Waste Incineration Directive, incineration plants must be designed to ensure that the flue
30 gases reach a temperature of at least 850 °C for 2 seconds in order to ensure proper breakdown of toxic organic substances. In order to comply with this at all times, it is required to install backup auxiliary burners (often fueled by oil), which are fired into the boiler (co-incineration) in case the heating value of the waste becomes too low to reach this temperature alone (mono-incineration).

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In the context of the present invention the term “Gasification” is to be construed as referring to a process that converts biomass- or fossil fuel-based carbonaceous

- materials into gases, including as the largest fractions: nitrogen (N_2), carbon monoxide (CO), hydrogen (H_2), and carbon dioxide (CO_2). This may be achieved by reacting the material, e.g. a hydrolysed biomass material, at high temperatures (typically $>700\text{ }^{\circ}C$), without combustion/incineration, via controlling the amount of oxygen and/or steam
- 5 present in the reaction. The resulting gas mixture is called syngas and may itself be used as a fuel due to the flammability of the H_2 and CO of which the gas is largely composed. Power can be derived from the subsequent combustion of the resultant gas, and is considered to be a source of renewable energy if the gasified compounds were obtained from a biomass material, e.g. a hydrolysed biomass material.
- 10 Gasification to syngas can be more efficient than direct incineration of the biomass material, e.g. a hydrolysed biomass material, because the syngas can be combusted at higher temperatures so that the thermodynamic upper limit to the efficiency defined by Carnot's rule is higher. Syngas may also be used as the hydrogen source in fuel cells, however the syngas produced by most gasification systems requires additional
- 15 processing and reforming to remove contaminants and other gases such as CO and CO_2 to be suitable for low-temperature fuel cell use, but high-temperature solid oxide fuel cells are capable of directly accepting mixtures of steam, and methane. Syngas is most commonly burned directly in gas engines, used to produce methanol and hydrogen, or converted into synthetic fuel. For some biomass materials, e.g. a
- 20 hydrolysed biomass material, gasification can be an alternative to landfilling and incineration, resulting in lowered emissions of atmospheric pollutants such as methane and particulates. Some gasification processes aim at refining out corrosive ash elements such as chloride and potassium, allowing clean gas production from otherwise problematic feedstock material. Gasification of fossil fuels is currently widely
- 25 used on industrial scales to generate electricity. Gasification can generate lower amounts of some pollutants as SO_x and NO_x than incineration.

In the context of the present invention the term "Pyrolysis" is to be construed as referring to a process by which a solid (or a liquid) material, e.g. a hydrolysed biomass

30 material, undergoes thermal degradation into smaller volatile molecules, without interacting with oxygen or any other oxidants. Pyrolysis, which is also the first step in gasification and incineration, occurs in the absence or near absence of oxygen, and it is thus distinct from incineration (burning), which can take place only if sufficient oxygen is present. The rate of pyrolysis increases with temperature. In industrial

35 applications the temperatures used are often $430\text{ }^{\circ}C$ or higher, whereas in smaller-scale operations the temperature may be much lower. Two well-known products created by pyrolysis are a form of charcoal called biochar, created by heating wood,

and coke (which is used as an industrial fuel and a heat shield), created by heating coal. Pyrolysis also produces condensable liquids (or tar) and non-condensable gases. If the purpose is to maximize the yield of liquid products resulting from biomass pyrolysis, a low temperature, high heating rate, short gas residence time process
5 would be required. For a high char production, a low temperature, low heating rate process would be chosen. If the purpose was to maximize the yield of fuel gas resulting from pyrolysis, a high temperature, low heating rate, long gas residence time process would be preferred.

- 10 In the context of the present invention the term "Torrefaction" is to be construed as a mild form of pyrolysis at temperatures typically between 200 and 320°C.

In the context of the present invention the term "Supercritical water oxidation" is to be construed as referring to the process of oxidation occurring in supercritical water when
15 an oxidant is added. A supercritical fluid (SCF) is any substance at a temperature and pressure above its critical point, where distinct liquid and gas phases do not exist, but below the pressure required to compress it into a solid. Water becomes supercritical at a temperature above app. 373°C and a pressure above app 220 bar.

- 20 In the context of the present invention the term "Supercritical water liquification" is to be construed as referring to the process of co-liquifying a given material with water at conditions where water is a supercritical state. Supercritical water liquefaction can be utilized for effective treatment of biomass in terms of material recovery. Cellulose, one of the main components of biomass, is completely dissolved in supercritical water.
25 Once dissolved, reaction of cellulose can take place swiftly by either hydrolysis and/or pyrolysis/torrefaction. The hydrolysis reaction, otherwise slower than pyrolysis/torrefaction due to the mass transfer limitation, is faster than decomposition in supercritical water, and efficient glucose recovery from cellulose has been shown to be possible. Once dissolved, a certain degree of super saturation can be maintained
30 when the solution is cooled down, whereby also swift hydrolysis by the use of enzymes has been shown to be possible. Lignin can be also converted into specialty chemicals by using supercritical cresol/water mixture as a solvent.

In the context of the present invention the term "Hydrothermal carbonization" is to be
35 construed as referring to a thermochemical treatment process where biomass is treated under hot compressed water to produce hydrochar. Although Bergius discovered hydrothermal carbonization as early as in 1913, it has been re-discovered

in the last few years, during which hydrothermal carbonization (HTC), has also become known as "hydrothermal pretreatment" or "wet torrefaction". Regardless, HTC is a thermochemical conversion technique that uses subcritical (liquid) water as a reaction medium for conversion of wet biomass and waste streams into a valuable carbon rich solid product. It is usually performed at temperatures ranging from 180°C to 280°C, at pressures slightly higher than water saturation pressure to ensure water is in a liquid state, and under an inert atmosphere.

In the context of the present invention the term "Hydrothermal oxidation" is to be construed as referring to a process involving treatment at temperatures and pressures below and above the critical point for water, i.e. app. 373°C and app 220bar, respectively. Subcritical water oxidation (SubCWO) achieves incomplete sludge oxidation (<95% COD removal) and produces high-strength liquors containing significant quantities of volatile fatty acids (VFAs). SubCWO also achieves efficient destruction of the organic component of sludge solids, resulting in significant mass and volume reductions. Supercritical wateroxidation (SCWO) on the other hand can completely oxidize the organic component of sludge (>99.9% COD reduction), produce high quality effluents and disposable ashes and air emissions.

In the context of the present invention the term "electrochemical processing" is to be construed as referring to processes involving the setting up of an electric field between anodes and cathodes to degrade and convert compounds. Bioelectrochemical processing, are electrochemical processes where biological activity on the electrodes assists or drives the degradation. Biocatalysts may also be used to accelerate a more efficient degradation. Such methods are also called Microbial electrosynthesis. Electrochemical processing designed for the waste water industry have been developed. These methods and the technology are still in the development phase, however, and more research and development is expected in the years to come. Thus, e.g. electrochemical oxidation of PFAS using various cathode/anode materials and catalysts has been subject to research and development for several years. Literature indicates that almost 99% of PFAS removal is possible with electrochemical treatment methods.

In the context of the present invention the term "biological processing for reduction of organic compounds" is to be construed as referring to biological processing, which utilizes the biological growth of microorganisms to digest and bind compounds in e.g. waste water by controlling the processing conditions. Important factors are

temperature, pH, dissolved oxygen, nutrient concentration and the content of toxic materials. These processes can be either aerobic or anaerobic, or can include arranging both aerobic and anaerobic processes in series. A range of biological processing methods are established to achieve a reduction in organic compounds as well as nutrient reduction. This includes but is not limited to activated sludge treatment systems, Bio-P treatment systems, MBR (Membrane Bio Reactors), MMBR (Moving Bed Biofilm processes). The anaerobic ammonium oxidation (anammox) process is one such process, which has been widely acknowledged as an environmentally friendly and time-saving technique capable of achieving efficient nitrogen removal.

Hence in the context of the present invention the term "biological processing for reduction of nutrients concentration" is to be construed as referring to e.g. anammox processes.

In the context of the present invention the term "chemical processing for reduction of nutrients concentration" is to be construed as referring to processing, which in different ways binds nutrients present in a material, e.g. a biomass material, chemically in order to remove (i.e. "strip") the nutrients and other compounds from the material. Typical chemical wastewater treatment processes are; chemical precipitation, ion exchange, neutralization, adsorption and disinfection processes. Evaporation technologies can also be applied to bind nutrients chemically. The water is evaporated and recovered as a condensate which is low on nutrients. The condensation heat is recovered internally in evaporators to reduce overall energy consumption. Different evaporation principles are available. Air strippers is another technology that can be applied to remove nutrients. The removal efficiency of nitrogen removal can be improved by increasing pH. Increased pH can be achieved by adding chemicals. Nitrogen removed by stripping can be recovered with chemicals to produce ammonia salts or by distillation as ammonia water.

In the context of the present invention the term "thermal processing for reduction of nutrient concentration" is to be construed as referring to processing, which at elevated temperature enhances the removal of nutrients present in a material, e.g. a biomass material being treated by chemical processing (see above). Thus, as an example the efficiency of Air strippers can be improved by increased temperature which can be achieved by adding heat in various ways, indirectly through heat exchangers or directly by steam (e.g. in the form of a so-called steam stripper).

In the context of the present invention the term “heat-exchangers” is to be construed as referring to any means, which may be used for transferring heat energy present in one material to another material, e.g. by the cooling of a material, e.g. a hydrolysed biomass material, by subjecting it to heat-exchange with water, which is then heated.

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In the context of the present invention the terms “retention time” and “average overall retention time” are to be construed as referring to Hydraulic Retention Time (HRT), defined as the ratio between the average reactor filling volume and the feed flow rate. In other words it represents the average amount of time that any sub-part of the

10 biomass material stay in a reactor or tank. It is calculated by dividing the average filling volume of a reactor (e.g. m³) by the influent flow rate (e.g. m³/day). In contrast the solids retention time (SRT) is the time the solid fraction of the biomass material in a treatment unit. It is the quantity of solids maintained in the unit divided by the quantity of solids coming out of the unit each day.

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In the context of the present invention the term “DS%” is to be construed as referring to the total dry solids content of a given material, including both the suspended solids and the dissolved materials, e.g. salts. Thus, the term “(DS%)”, also called “dry-matter content” is to be construed as referring to the percentage of solids in a mixture, e.g. a
20 “biomass material”. The higher this proportion, the drier the mixture. One unit of DS content is % by weight. Expressed as a ratio of weights obtained before and after a drying process, in which a sample of the material is placed in an oven at a temperature of 105 °C until a steady mass is obtained. Drying at 175-185°C and comparing the result obtained by drying at 105°C enables the evaluation of the content of
25 crystallisation water of certain salts, e.g. hydroxides, which might be part of the sample.

Heating the residue from the 105°C drying process to 550°C for two hours in a preheated and thermostatically controlled muffle oven enables the determination of the
30 part of the total dry solids, which are volatile at a temperature of 550°C. For most biomass materials this can be considered an approximation of the organic matter content of the material, also referred to as volatile solids (VS). The VS is usually expressed as a % of dry-matter.

35 The part of a biomass material sample that are volatile at temperatures between 550 and 900°C, will in most scenarios mainly consists of CO₂ produced by the decomposition of carbonates contained in the biomass material.

Hence, in the context of the present invention the term "VS%" is to be construed as referring to the % of the total dry solids content (DS%), which is volatile at a temperature of 550°C.

5

In the context of the present invention the term "suspended solids" (SS) is to be construed as referring to solid particles of any origin which remain in suspension in water as a colloid or due to motion of the water. Suspended solids can be removed by sedimentation if their size or density is comparatively large, or by filtration. Within the technical field of the present invention the term Total Suspended Solids (TSS) is commonly used to refer to particles larger than 2 microns found in water. Both SS and TSS can be reported as mg/L, ppm or %. The amount of suspended solids (SS) or total suspended solids (TSS) may be measured by the use of e.g acoustic or ultrasonic type instrument, or gamma type instrument, or by measuring the turbidity of the sample in question.

In the context of the present invention the term particle size distribution is to be construed as referring to the particle-size distribution of particles dispersed in a sample, in the form of a list of values or a mathematical function that defines the relative amount, typically by mass, of particles present according to their size. In the context of the present invention the term particle shape distribution is to be construed as referring to the particle-shpae distribution of particles dispersed in a sample, in the form of a list of values or a mathematical function that defines the relative amount, typically by mass, of particles present according to their shape.

25

The particle size distribution and/or the particle shape distribution of a sample may be determined by a number of different techniques, such as Sieve analysis, Air elutriation analysis, Photoanalysis, Optical granulometry, Optical counting methods, Electroresistance counting methods, Sedimentation techniques, Laser diffraction methods, Laser Obscuration Time" (LOT) or "Time Of Transition" (TOT) and/or Acoustic spectroscopy or ultrasound attenuation spectroscopy.

In the context of the present invention the term "FOS/TAC ratio by the Nordmann method" is to be construed as referring to measurements of volatile organic acids (FOS) and total inorganic carbon (TAC) (i.e. carbon buffer capacity) by what is normally referred to as the Nordmann method. The FOS/TAC ratio is a commonly

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applied measurement for observing stability and indicating if corrective action must be taken in an anaerobic digestion process of e.g. a biogas plant.

To find the FOS/TAC value, a representative sample of the relevant biomass material
5 is used. All particulate matter must be removed by filtration or centrifugation, and all sample preparation must be performed in the same manner. Typical sample volume of the substrate is 20 mL but may be diluted with deionized water if there is an insufficient amount. Note that the TAC equation must be altered to account for the dilution.

10 First, TAC (in mg CaCO_3/L) is measured by titrating the sample to pH 5.0 with 0.1 N sulphuric acid and can be calculated by using the following equation:

$$\text{TAC} = (\text{EP1} \times \text{Concentration of titrant} \times 50045) / (\text{Volume of sample})$$

15 where EP1 is the volume of the titrant at pH 5.0 in mL. If Ctitrant is 0.1 N and Volume of sample is 20 mL, the equation can be simplified to:

$$\text{TAC} = \text{EP1} \times 250 \text{ [mg/L CaCO}_3\text{]}$$

20 Following the titration to calculate TAC, the Nordmann method is used to determine the FOS (in mg/L Hac) content by titrating a 20 mL sample from pH 5.0 to pH 4.4 using 0.1 N sulphuric acid. Using the following equation where B is the acid consumed in mL (i.e. volume of titrant at pH 5.0 – volume of titrant at pH 4.4).

25 $\text{FOS} = [(B \times 1.66) - 0.15] \times 500 \text{ [mg/L Hac]}$

In general, a FOS/TAC value of 0.3-0.4 is considered optimal. However, every digester has a unique optimal ratio. Above 0.4, there is normally excessive biomass input and below 0.3, there is normally too little biomass input.

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In the context of the present invention the term “amount of dissolved organic carbon”, also sometimes called DOC, is to be construed as referring to the fraction of organic carbon in a given biomass material, which can pass through a filter with a given pore size, typically between 0.22 and 0.7 micrometers. The fraction remaining on the
35 relevant filter is then called particulate organic carbon (POC).

In the context of the present invention the term “amount of dissolved organic nitrogen”, also sometimes referred to as (DON), is to be construed as referring to that subset of the dissolved organic carbon (DOC) pool that also contains N. Dissolved inorganic nitrogen (DIN) is comprised of nitrate plus nitrite and ammonium. Total dissolved
5 nitrogen (TDN) is comprised of dissolved inorganic nitrogen (DIN) and dissolved organic nitrogen (DON). Because there is no reliable way to measure DON directly, it is usually calculated from measured TDN and DIN values ($DON = TDN - DIN$).

As opposed to DOC, dissolved organic matter (DOM) refers to the total mass of the
10 dissolved organic matter. That is, DOM also includes the mass of other elements present in the organic material, such as nitrogen, oxygen and hydrogen. DOC is a component of DOM and there is typically about twice as much DOM as DOC.

As already explained above, the methods, systems, process equipment and plants
15 employing Thermal Hydrolysis Processes (THP) of the present invention includes several improvements compared with prior art thermal hydrolysis processes. First of all, the methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention enable stable operation of thermal hydrolysis systems at high apparent viscosity and variable high dry solids
20 content.

Thermal hydrolysis operated at high dry solids concentration is important in order to minimize specific energy consumption (e.g. measured as kg steam/tonne dry solids).

25 The methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention rely on the key finding that apparent viscosity, e.g. static yield stress and/or dynamic yield stress, rather than DS% is the key limitation for operating thermal hydrolysis systems at high dry solids concentration and thus achieving a low specific energy consumption, and that different substrates
30 have significantly different rheological behaviour.

As apparent viscosity, e.g. static yield stress and/or dynamic yield stress, increases with dry solids content and decreases with temperature, it is highly beneficial to monitor the actual rheological behaviour of the specific substrate mixture being subject
35 to thermal hydrolysis treatment and continuously adjust the process accordingly in order to continuously minimize the specific energy consumption.

The adjustments relate to both dry solids content in upstream dewatering and dilution rate of THP feed stream, as well as preheating of dilution water. The rheology behaviour of all substrates are influenced by not only dry solids content, but also temperature. The methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention present invention rely on adjusting both feed temperature and dry solids content based on actual rheology behaviour of the substrate being treated in a thermal hydrolysis process.

As co-digestion has become increasingly popular over the recent years, substrates or substrate mixtures now-a-days treated by thermal hydrolysis could be of significant different apparent viscosity, e.g. static yield stress and/or dynamic yield stress. When different substrates are mixed at different ratio's the apparent viscosity, e.g. static yield stress and/or dynamic yield stress, of the resulting mixture will also change depending on the rheology behaviour of the resulting mixture, which might differ significantly from the rheology behaviour of the individual substrates being mixed. The methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention enables continuous monitoring of the apparent viscosity, e.g. static yield stress and/or dynamic yield stress, of the mixture inside the thermal hydrolysis process, and makes it possible to optimize both mixture rate, pre-heating as well as dilution rate in order to minimize specific heat consumption during the thermal hydrolysis process.

Throughout a thermal hydrolysis system, where temperature is increased and reduced stepwise the pre-heating step quickly reach its limitations with regards to apparent viscosity, e.g. static yield stress and/or dynamic yield stress. The reason behind this, is that sludge and most other substrates reaches a higher apparent viscosity, e.g. static yield stress and/or dynamic yield stress, at lower temperature. Heat recovery and subsequent pumping can be challenging in case the design is not adequate.

Prior art does not describe this problem. Consequently, throughout the years, methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) have suffered from operation at high apparent viscosity, e.g. static yield stress and/or dynamic yield stress, for certain substrates. The methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention includes a design of a pre-conditioning system, that increases the feed temperature and enable operation at high apparent viscosity, e.g. static yield stress and/or dynamic yield stress, and thus facilitate for high dry solids thermal

hydrolysis. The system also includes a monitoring system to ensure compliant processing conditions.

The methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention optionally includes a pre-conditioning device to further reduce apparent viscosity, e.g. static yield stress and/or dynamic yield stress, (due to both increased temperature and applied shear forces) enabling operation at higher dry solids content. This addresses challenges in both the THP feed system due to the high apparent viscosity, e.g. static yield stress and/or dynamic yield stress, as well as reducing the specific heat consumption in the thermal hydrolysis process. The reason for reduced heat consumption in the thermal hydrolysis process is both the higher dry solids concentration, as well as the elevated feed temperature. The pre-conditioning device will be perfectly matched with the cooling demand usually required for hydrolysed sludge and thus enable a more cost efficient heat recovery that directly influences the specific steam consumption required in thermal hydrolysis processes. The pre-conditioning device may also receive preheated dilution water from other sources depending on what is most cost efficient.

As a further advantage, the methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention enables these to be self-optimizing through controlling the pre-heating and dilution rate depending on measured apparent viscosity, e.g. static yield stress and/or dynamic yield stress, through an advanced monitoring system. Furthermore, in case of co-digestion, the measured apparent viscosity, e.g. static yield stress and/or dynamic yield stress, can be used to optimize the ratio of different substrates throughout the process cycle.

The methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention addresses several aspects to secure the functionality of thermal hydrolysis processes, some of which will be explained in detail in the following.

The methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention enable both feed and operation of thermal hydrolysis processes with substrates with high apparent viscosity, e.g. static yield stress and/or dynamic yield stress, through a specifically set of design features and

process solutions inside and upstream and/or downstream the thermal hydrolysis process combined with specific monitoring to secure stable operation.

The methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention allow for optimization and control of thermal hydrolysis processes based on rheology rather than dry solids content.

The methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention rely on continuous monitoring and analysing of substrate rheology behaviour through softsensing enabled by specifically applied design and instrumentation of the thermal hydrolysis system as well as upstream and downstream the thermal hydrolysis system.

The methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention allow for operation of THP systems at highest possible dry solids content, while at the same time reducing the specific energy demand. This builds on the finding that apparent viscosity, e.g. static yield stress and/or dynamic yield stress, is a limiting factor for operating THP plants at high dry solids. The invention uses the continuously monitored rheology data and thermal hydrolysis performance data as information to learn the thermal hydrolysis systems to self-adjust the dry solids content at highest possible dry solids level.

The methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention allow for the prediction of dry solid content (DS%) and Volatile Solids Content (VS%) based on rheology data measured for a given biomass material throughout the process. It does this by establishing a series of soft sensors throughout the thermal hydrolysis process as the rheology changes throughout the process and the continuous measurement of rheology characteristics allows to the use of these rheology data to predict DS% and VS%, specific energy content (COD/VS) and/or nitrogen content of the biomass material, e.g. sludge, being processed. This again allows for the optimization of apparent viscosity, e.g. static yield stress and/or dynamic yield stress, throughout the process by applying the correct dilution rate at the right temperature. It, furthermore, allows for self-correction of the predicted DS%, VS%, COD/VS and/or N-content by serial measurement and accompanying instructions to the operators to when and how to sample to best support the self-calibration.

As mentioned above apparent viscosity, e.g. static yield stress and/or dynamic yield stress, normally decreases with increasing temperature. The methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention allow for adjustment of sludge temperature through a more extensive

5 heat recovery to enable stable operation up to the maximum apparent viscosity, e.g. static yield stress and/or dynamic yield stress, limit of the thermal hydrolysis process without unreasonable safety margins having to be applied. This is done by recovering heat available at the back end of the process to be used at the front end of the process so that the incoming feed temperature to the Thermal Hydrolysis System is increased

10 and the discharge temperature is decreased.

As mentioned above the methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention build on the finding that apparent viscosity, e.g. static yield stress and/or dynamic yield stress, vary

15 significantly both for a given a substrate and between different substrates. In case of operating at the maximum apparent viscosity, e.g. static yield stress and/or dynamic yield stress, limit for a THP process, this in itself poses a risk to enter into periods with both operational difficulties as well as insufficient thermal hydrolysis. The methods, systems, process equipment and plants employing Thermal Hydrolysis Processes

20 (THP) of the present invention allow for the inclusion of a self-correcting system into the THP process to avoid operational disturbances in case of varying apparent viscosity, e.g. static yield stress and/or dynamic yield stress, in the substrate or mixture of substrates being treated. In case the process monitoring reveals an unfavourable high apparent viscosity, e.g. static yield stress and/or dynamic yield

25 stress, the system will automatically adjust the apparent viscosity, e.g. static yield stress and/or dynamic yield stress, through a stepwise dilution with preheated water in a pulper feed system and in the pulper circulation/reactor feed system. Preheating is preferably achieved by cooling of hydrolysed sludge at the back end of the process. Depending on how much the sludge is preheated by an external heat source and

30 depending on the THP process, the over-all steam consumption in the thermal hydrolysis system may typically decrease in the range of 3-15% as a result of such preheating.

In one embodiment of the methods, systems, process equipment and plants

35 employing Thermal Hydrolysis Processes (THP) of the present invention these include recycling a flow of preheated substrate from the pulper to a pre-conditioning system

applied at the front end of the thermal hydrolysis process in order to reduce apparent viscosity, e.g. static yield stress and/or dynamic yield stress, in the pulper feed line.

As should be clear from the above, even thermal hydrolysis processes relying on a
5 substrate of a relatively constant composition may be vulnerable when operating on substrates at high apparent viscosity, e.g. static yield stress and/or dynamic yield stress, if the temperature of the material, e.g. biomass material, to be treated in the process cannot be kept within certain predetermined limits. Hence, in a preferred aspect the methods, systems, process equipment and plants employing Thermal
10 Hydrolysis Processes (THP) of the present invention includes a novel design of a pre-heating vessel (pulper) particularly suited to enable operation at elevated apparent viscosity, e.g. static yield stress and/or dynamic yield stress.

Some of the key elements of the design of this preferred pre-heating vessel (pulper
15 (s)) is to utilize the discovery that in a thermal hydrolysis pulper, fitted for recovery of downstream flash steam, the upper section of the vessel is warmer and more homogeneous than the bottom section of the vessel, coupled with the fact that operation becomes increasingly difficult if the temperature of the material in the pulper discharge line is not kept relatively constant. Steam or recovered flash steam is
20 injected into the lower part of the vessel and thus heat the substrate as the steam/flash steam raises to the upper section of the vessel. This leads both to warming up cold sludge and to transferring warm sludge towards the upper part of the vessel, while a larger proportion of the cold sludge is found in the lower part of the vessel. The injection of steam in the lower part of the vessel causes a mixing effect as it travels
25 through the liquid and condenses in contact with colder liquid. In most existing pulper vessel designs this injection of steam is done by steam lances. Even if different design of steam lances exists, it is in the methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention preferred to orient the tip of the lances in such an angle that it contributes in creating a swirl in both
30 horizontal and vertical plane. In this preferred aspect substrate may (or may not) be circulated on the vessel by pumping substrate from an elevated warmer part of the vessel and reintroduced into the colder bottom section and/or into the top section together with cold substrate, preferably through an extruder or a similar distribution system. Also any extruder may optionally be located outside the pre-heating vessel,
35 and may optionally be replaced with a recycle flow back to a pre-conditioner.

Optionally, the methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention in the above-mentioned preferred aspect includes a specifically designed Pre-conditioning device upstream the pulper (in connection with the pulper feed system) to enable efficient dilution, pre-heating

5 mixing and recovery of heat from downstream hydrolysed sludge. This Pre-conditioning device, applied at the front end of a thermal hydrolysis system, thereby becomes an integrated part of the THP "train" and may serve as a buffer between any upstream pre-dewatering system or substrate processing or substrate reception system and the actual thermal hydrolysis system. The pre-conditioning system links

10 with the back end of the thermal hydrolysis system by capturing surplus heat that is available in warm hydrolysed sludge and recovers this heat to increase the feed temperature of cold substrate entering the thermal hydrolysis system.

The methods, systems, process equipment and plants employing Thermal Hydrolysis

15 Processes (THP) of the present invention use rheology data from hydrolysed sludge measured on e.g. a digester feed line and/or pre-cooler and convert this into expected DS%, VS%, COD/VS and/or N-content and thereby enables the calculation of and the control of the digester loading rate based on rheology data of the biomass material at different stages before and during the THP process. In this way it is possible to control

20 the digester loading rate not only based on DS% and VS% loading rate, but also use the rheology data measured to predict specific energy content (COD/VS) of the biomass material to have the full control with the digester feed rate, thereby essentially eliminating any risk of overloading the digester. Additionally, measuring Nitrogen content may assist in controlling the nitrogen load of the digester.

25

In a preferred embodiment, the methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention include an extensive digester monitoring program, which directly reduce digester feed and thus THP feed in order to avoid overload. As the methods, systems, process equipment

30 and plants employing Thermal Hydrolysis Processes (THP) of the present invention will adjust DS% in THP based on apparent viscosity, e.g. static yield stress and/or dynamic yield stress, a constant volumetric feed flow for the digester will not provide a constant VS loading of the digester. In order to avoid unintended overloading of the digester, the system needs to self-adjust in case of any indication of digester

35 overloading. This becomes increasingly important when digesters are operated at high dry solids loading rate with short retention time.

Similarly, the continuous conversion of rheology data, measured at different points of the THP “train”, into energy content, enables the control of the actual energy feed rate to the digester.

- 5 Thus, as a result of the methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention, the energy feed rate for the digester can be controlled by monitoring rheology. There have previously been different attempts to correlate rheology with dry solids content and even volatile solids content, and instruments have been developed for this purpose. These all fall short ,
- 10 however, due to the fact that not all dry solids and volatile solids utilized for digester feed, do necessarily have the same energy content. The methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention therefor solves the problem that feeding digesters based only on a measure of dry solids or volatile solids, fails to take into account that different substrates have
- 15 different specific energy content pr unit of dry solids and pr unit of volatile solids. Hence in contrast to the prior art, the methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention make use of a biomass materials rheological behaviour to predict its specific energy content.
- 20 Consequently, the methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention can be used to control the energy feed rate of the digester in addition to controlling the dry solids loading, the volatile solids loading and the nitrogen loading.
- 25 As described further below, this is primarily achieved through the discovery that there is a close relation between the so-called apparent viscosity, e.g. static yield stress and/or dynamic yield stress, of a given biomass material, “ τ_o ” and/or “ τ_y ”, respectively, and the specific energy content.
- 30 The discovery of this relationship inter alia paves the way for the optional addition of chemical agents into the biomass material in the pre-conditioner in order to a) reduce apparent viscosity, e.g. static yield stress and/or dynamic yield stress, and/or b) start an exotherm reaction that increases feed temperature and thus reduces apparent viscosity, e.g. static yield stress and/or dynamic yield stress, and decrease specific
- 35 heat consumption in the thermal hydrolysis step. Also, from a more general perspective the discovery of this relationship paves the way for the optional addition of chemical agents known to directly or indirectly influencing other properties of the

biomass material, e.g. chemical or biochemical composition, microbial composition or content, cellular structure, particle size distribution or particle shape distribution, known to directly or indirectly influence the apparent viscosity, e.g. static yield stress and/or dynamic yield stress, of the biomass material .

5

It also allows for the possibility to monitor digester performance through key indicators to optimize the loading of the digesters by self-learning. Thus, even if it has been well known that high dry solids digestion may be enabled through thermal hydrolysis, it has until now not been known how the thermal hydrolysis system may be fitted to self-learn

10 how to best optimize the digester loading rate based on the continuous measurement of apparent viscosity, e.g. static yield stress and/or dynamic yield stress, at different points of the THP process. By measuring apparent viscosity, e.g. static yield stress and/or dynamic yield stress, at several places in the process where apparent viscosity, e.g. static yield stress and/or dynamic yield stress, has changed significantly due to

15 the different stages of the thermal hydrolysis process, the measurement itself at each point takes place under significantly different conditions. Hence, in preferred embodiments measurement that are made under different conditions (i.e. different stages of the THP process) are utilized for cross-calibrating the measurements. Furthermore, in case this cross-calibration is not successful, the methods, systems,

20 process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention may allow for the operator to receive a warning to assist with the calibration through additional sampling and login of sampling results into the control and monitoring system where the sampling data is used to assist the calibration.

25 Digester loading is normally controlled by sampling of DS% and VS% and controlling the feed flow to the digester manually. The methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention rather use apparent viscosity, e.g. static yield stress and/or dynamic yield stress, measured continuously at several points throughout the process, which are subsequently

30 converted into calculated digester loading rates and introduce both a self-improving cross-calibration system to reduce error margin and a self-controlling system to avoid overloading of the digester and optimize the AD process. In this way the methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention enable control of the COD/VS loading rate (rather than

35 simply the DS% and/or VS% loading rate) due to the relationship that has been determined between apparent viscosity, e.g. static yield stress and/or dynamic yield stress, and energy content measured as COD/VS.

In preferred embodiments of the methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention, the integrated self-controlling system includes monitoring of parameters such as pH, Gas
5 production, methane content and/or the FOS/TAC ratio of the digester. When reaching certain levels and/or rates in the raisin of pH, FOS/TAC and or CH₄ concentration the thermal hydrolysis loading rate would then automatically adjust the loading rate down to an acceptable level.

10 In this way the automatic self-controlling systems of the methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention facilitates demand-based digester operation through maximizing biogas production during periods with high value of the biogas, e.g. demonstrated by waste
water utilities in the UK to capitalize on fluctuating electricity prices in UK. Hence, the
15 methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention enables maximized and controlled loading of both the thermal hydrolysis step and a downstream digestion process through monitoring the limiting factor for the thermal hydrolysis step, which is apparent
viscosity, e.g. static yield stress and or dynamic yield stress, in the THP. In addition,
20 the apparent viscosity, e.g. static yield stress and/or dynamic yield stress, levels monitored may be converted into values for the DS and VS loading rate of the digester.

Similarly, in the methods, systems, process equipment and plants employing Thermal
25 Hydrolysis Processes (THP) of the present invention the rheology measurement may be used to activate dilution prior to the pre-cooler in order to optimize heat transfer and thus total max capacity of the pre-cooler.

In certain embodiments of the methods, systems, process equipment and plants
30 employing Thermal Hydrolysis Processes (THP) of the present invention a proportion of the digested and dewatered cake may be recycled back to pulper feed. Digested cake can be of high apparent viscosity, e.g. static yield stress and/or dynamic yield stress, similar to waste activated sludge. Digested cake also behaves as a non-Newtonian fluid. Due to the thermal hydrolysis process, the cake is well dewatered and
35 the apparent viscosity, e.g. static yield stress and/or dynamic yield stress, is high, and even if this would make it difficult to transport and mix into the pulper feed line in most systems, the methods, systems, process equipment and plants employing Thermal

Hydrolysis Processes (THP) of the present invention are well suited to recycle high dry solids cake and mix it into the pulper feed line the same way as for feed sludge. Recycling of digested dewatered cake, have potential to improve energy and mass balance through both increasing the net energy surplus and further reducing total
5 digested cake leaving the system.

Disposal cost can be high, and reduction of cake quantity can have significant impact on the overall economy and operation expenses of a THP based system/plant. In one example of the methods, systems, process equipment and plants employing Thermal
10 Hydrolysis Processes (THP) of the present invention, this particular embodiment of the invention would increase biogas production in the magnitude of 20% and reduced cake production in the magnitude of 15%. The overall THP system would however consume more heat due to the return flow of digested cake. In case biogas is consumed to produce the increased heat consumption, the net energy surplus could,
15 however, be approximately 8%. In another example this particular embodiment of the invention would increase biogas production in the magnitude of 10-15% and reduced cake production in the magnitude of 10%. In case biogas is consumed to produce the increased heat consumption, the net biogas surplus could in some cases be approximately 5-6%.

20 In a further embodiment of the methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention compressed process gases may be used to 1) reduce pressure drop in the pulper feed line and/or 2) improve digester performance, e.g. if the compressed process gasses are de-
25 aerated in the pulper, and injected into the digester using a compressor. The process gases will be odorous and contain harmful substances that can be toxic even in small concentrations. It is thus important to handle the process gases with care in a closed system. The processes gases should not in any case be emitted directly. Hence in this embodiment the methods, systems, process equipment and plants employing Thermal
30 Hydrolysis Processes (THP) of the present invention include a closed system that inject the process gases into the digester for 1) adsorption into the liquid face and 2) biological treatment. Some of the organic compounds precent in the process gases as well as oxygen possibly released through deaeration will further enhance the digester performance. The addition of oxygen into the pulper or pulper feed line enable
35 optimization of the digestion process.

The most important aspect of a pulper design according to the present invention, enabling operation at high dry solids with full heat recovery, is the location of the discharge nozzle on the pulper. The volume below the outlet nozzle for the pump(s) should be ≥ 1.6 average reactor fill volume. The volume above the nozzle should
5 preferably be >1 average reactor filling volume plus some safety margin above the nozzle but may be larger, such as 1.2, 1.4, 1.6 or 1.8 average reactor filling volume.

In addition, the inclusion of an extruder to split incoming cold sludge into smaller segments is part of a preferred embodiment of a pulper in accordance with the present
10 invention.

Pre-heating of substrate prior to thermal hydrolysis processes is beneficial in order to reduce the specific energy consumption. Thermally hydrolysed sludge will leave the hydrolysis process at a high temperature unless it is diluted with cold water. Pre-
15 heating of the biomass provides an opportunity for cost efficient recovery of surplus heat available in the hydrolysed sludge that will otherwise be left unused at high cost. The methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention can use incoming cold substrate as a source of cooling of already hydrolysed substrate and at the same time recover more heat,
20 and reduce specific heat consumption in the thermal hydrolysis process.

The possibility to perform the hydrolysis at the highest possible dry solids concentration is important in order to minimize specific energy consumption during the thermal hydrolysis process. An important barrier up to now for operating at high dry
25 solids is limitations related to processing of substrates at high apparent viscosity, e.g. static yield stress and/or dynamic yield stress. Most biomass materials are characterised by higher apparent viscosity, e.g. static yield stress and/or dynamic yield stress, at higher dry solids content (DS%). Also, varying apparent viscosity, e.g. static yield stress and/or dynamic yield stress, in substrates normally makes it necessary to
30 be on the safe side with regards to dry solids content (DS%) to avoid operational challenges and interruptions during day-to-day operation. This safety margin in many cases comes at an unreasonably high operational cost due to the significant higher energy consumption associated with thermal hydrolysis of dilute substrates. There are no known thermal hydrolysis processes that continuously monitor and optimize the
35 combination of dry solids content, apparent viscosity, e.g. static yield stress and/or dynamic yield stress, and heat recovery. The methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention

enable continuous monitoring of the rheology behaviour of substrates by a specifically applied design. This design is an integrated part of the THP process and does not rely on traditional apparent viscosity, e.g. static yield stress and/or dynamic yield stress, measuring instruments, which are prone to give rise to difficulties when applied to

5 inhomogeneous substrates with high content of fibers, sand, grit, hair, twigs, etc. Instead of using such commercially available instruments, apparent viscosity, e.g. static yield stress and/or dynamic yield stress, is, in the methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention, monitored continuously throughout the process by monitoring key

10 performance indicators applied and integrated with the process. This way of monitoring enables a robust optimization of both the dry solids content and the heat recovery rate simultaneously.

In addition to a stepwise monitoring of apparent viscosity, e.g. static yield stress and/or

15 dynamic yield stress, throughout the process a continuous monitoring of the digester performance enables full control over the dry solid loading throughout the process and enables safe operation of both the THP and any downstream anaerobic digestion process without unnecessary safety margins.

20 Several factors influence on the apparent viscosity, e.g. static yield stress and/or dynamic yield stress, of a substrate:

- The Rheological characteristic of a substrate or mix of substrates
- Dry solids content (DS%)
- 25 • Temperature

Factors influencing specific heat consumption of the thermal hydrolysis are:

- Dry solids content (DS%)
- 30 • Volatile solids content (VS%)
- Chemical composition
- Feed temperature
- Internal heat recovery rate of the thermal hydrolysis system

35 Several instruments for continuously monitoring dry solids content of a biomass material are currently available in the market. The use of these instruments is, however, difficult for substrates with high apparent viscosity, e.g. static yield stress

and/or dynamic yield stress, and in situations when rheological behaviour changes over time. A typical challenge is that the available instruments are inaccurate and that signals tend to drift unless the instrument is frequently calibrated. Hence, the methods currently available for monitoring of DS% for continuous adaption of the dry solids

5 content prior to thermal hydrolysis is not considered sufficiently reliable for controlling the thermal hydrolysis process fully. Moreover, as explained above, the present invention is based on the discovery that it is not the dry solids content that is the actual limiting factor for the thermal hydrolysis process, but rather the apparent viscosity, e.g. static yield stress and/or dynamic yield stress. In light hereof the present invention

10 describes a novel design to enable continuous monitoring of apparent viscosity, e.g. static yield stress and/or dynamic yield stress, in a thermal hydrolysis process and the use of the data obtained to continuously optimize the operation.

Through optimized pre-heating and dilution rate, the specific heat consumption of a

15 THP system can be minimized significantly. When increasing the dry solids content, it is necessary to be able to control the apparent viscosity, e.g. static yield stress and/or dynamic yield stress, which is a limiting factor for processing substrates. This is in the methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention done by monitoring the rheological

20 behaviour of the biomass material in the THP feed system as well as monitoring the rheological behaviour of the biomass material at different stages internally inside the thermal hydrolysis system and adjusting the dry solids content to a level that still ensures high heat recovery rate.

25 The pre-heating will, in methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention, take place in an upstream pre-conditioning device. Sludge and similar substrates that have a typical non-Newtonian behaviour, will reduce its apparent viscosity, e.g. static yield stress and/or dynamic yield stress, when exposed to shear forces. A specific feature of the

30 design of the methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention is that the pre-conditioning device introduces shear forces to the substrates and through that reduces the apparent viscosity, e.g. static yield stress and/or dynamic yield stress. As a result of the reduced apparent viscosity, e.g. static yield stress and/or dynamic yield stress, the pumping to

35 the next processing step in the thermal hydrolysis system can be done at a lower resistance in the pipeline. As a result of the reduced apparent viscosity, e.g. static yield stress and/or dynamic yield stress, the specific pressure drop will decrease and

thus the power consumption required for pumping decrease accordingly. The reduced apparent viscosity, e.g. static yield stress and/or dynamic yield stress, due to the shear forces applied to the substrate, in methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention, will decrease
5 over time and the apparent viscosity, e.g. static yield stress and/or dynamic yield stress, of the biomass material will revert back to the same apparent viscosity, e.g. static yield stress and/or dynamic yield stress, level as before the shear forces were applied. Hence, the retention time in the transfer pipe should, in methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention, be kept as low as possible by minimizing the length of the transfer
10 pipe.

Surplus heat from pre-coolers downstream the thermal hydrolysis system will, in the methods, systems, process equipment and plants employing Thermal Hydrolysis
15 Processes (THP) of the present invention, be recovered in the Pre-conditioning device. In case hydrolysed sludge is pre-cooled to a degree corresponding to a $\Delta T = 20^\circ\text{C}$, there should be sufficient heat to increase feed temperature of the biomass material in the pre-conditioning device with more than 20°C , e.g. from 15°C to 35°C . An increase of the temperature of a biomass material by 20°C would, without changing the DS%,
20 reduce the specific steam consumption with about 20%, provided that the THP is designed to handle the corresponding temperatures and pressures achieved throughout the process.

Pre-cooling can, in methods, systems, process equipment and plants employing
25 Thermal Hydrolysis Processes (THP) of the present invention, be done in several ways. The most common way of pre-cooling is to use tube-in-tube heat exchangers. Another and more advanced way of pre-cooling would be to apply a flash-cooler using vacuum to reach preferred temperature. An advantage with flash coolers is that they eliminate the challenges with heat transfer coefficient dependency on apparent
30 viscosity, e.g. static yield stress and/or dynamic yield stress. For substrates showing high apparent viscosity, e.g. static yield stress and/or dynamic yield stress, heat transfer is low. When operating at the maximum apparent viscosity, e.g. static yield stress and/or dynamic yield stress, limit, as in the methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present
35 invention, it is beneficial to design coolers so that the required heat surface area is not dependent on sludge apparent viscosity, e.g. static yield stress and/or dynamic yield stress. In a flash cooler, the heat transfer will take place by condensation of steam on

heat surfaces rather than by sludge being in contact with heat surfaces, which is the case in standard heat exchanges used in the industry such as e.g. tube in tube or spiral type heat exchangers. For any cooler design, excess heat can be used for pre-heating dilution water for the pre-conditioner. For coolers lowering temperature to a

5 low level, e.g. 40 or 50°C, high temperature excess heat will not be available unless lifting the heat assisted by other technologies. However, this low temperature excess heat may still be utilized for preheating.

Recovered heat using any cooler design can be recovered upstream the thermal hydrolysis system either by adding hot water in the pulper, or upstream the pulper by

10 mixing it with a substrate at high dry solids above 8% DS, preferably at least 12% DS, preferably above 18% DS or even more preferably above 20% DS. Recovered heat may also be used for preheating polymer/water in upstream pre-dewatering or thickening processes and, thus, both assist in improving dewatering properties that can be achieved at elevated temperature and assist in improving the overall heat

15 balance across the thermal hydrolysis process due to increased feed temperature to the thermal hydrolysis system.

As incoming sludge at high dry solids has a poor heat transfer due the high apparent viscosity, e.g. static yield stress and/or dynamic yield stress, it is preferred, in the

20 methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention, to pre-heat dilution water that is then mixed into the incoming substrate received from upstream dewatering devices or imported from other sites.

25 An important task for the pre-conditioning device, of the methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention, is to produce a well-mixed and homogenous substrate for A) pumping to downstream THP at lowest possible pressure drop (and energy consumption) and B) reduce the apparent viscosity, e.g. static yield stress and/or dynamic yield stress, in

30 sludge prior to entering the THP pulper, thereby reducing the need for mixing in the pulper and enabling operation at higher dry solids by the use of minimum possible power consumption.

In methods, systems, process equipment and plants employing Thermal Hydrolysis

35 Processes (THP) of the present invention, pre-heated water will be added to the pre-conditioner device with the objective of producing a well mixed substrate. The pre-conditioner device, of the methods, systems, process equipment and plants employing

Thermal Hydrolysis Processes (THP) of the present invention, could either be an integrated part of the THP feed pump or an upstream mixer. In one possible embodiment of the design, the mixing is done in a screw conveyor having a larger, preferably at least 1.5 times larger, conveying capacity than the subsequent THP feed pump. The substrate will thus be leaking back in a loop, whereby the substrate will be mixed. The higher relation between conveyor capacity and pump capacity, the more intense the mixing will be and the better pre-conditioned the substrate will be prior to entering the THP train. Typically, the pump capacity should be in the range of 50-90% of the conveyor capacity in order to provide a sufficiently high relation between the conveyor capacity and the pump capacity. The average hydraulic retention time in the mixer should be at least in the range of 1-15 minutes to secure a well-mixed substrate. The correct/sufficient hydraulic retention time in the mixer will depend on the apparent viscosity, e.g. static yield stress and/or dynamic yield stress, of the substrate, the temperature, and the dilution rate of the mixer. For a ratio of dilution water vs cold substrate in the range of 0.025:1 to 5.0:1 the retention time in the mixer should typically be 1-15 minutes. The higher the pump capacity vs the conveyor capacity, the longer a retention time would be required to achieve efficient operation. With low pump capacity vs conveyor capacity, the mixing intensity would be high and a lower retention time would be required.

Another possible embodiment, in the methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention, is a designated mixer in the bottom of the sludge silo. This mixer could have several possible designs such as shaftless screw conveyor, helical screw conveyor or a paddle mixer.

One possible solution, in methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention, is to make use of a flexishaft pump and to do all the mixing in an upstream conveyor being a part of the sludge silo. This would reduce the cost of the pump as the mixing section is large and heavy.

Another possible solution, in methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention, is to make use of a combined screw and mixing shaft.

Ensuring that the substrate is well mixed and pre-heated prior to entering the THP is also beneficial for the THP operation in general, as less mixing energy in relation to the THP pulper will then be required for efficient operation.

- 5 For some substrates, the addition of chemicals could be beneficial for pre-conditioning in relation to any downstream anaerobic digestion (as well as other fermentation processes). In such embodiments, of methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention, the pre-conditioning device needs to be designed to tolerate the chemicals used for pre-
10 conditioning as well as the temperatures it may be exposed to. In particular chemicals that reduce apparent viscosity, e.g. static yield stress and/or dynamic yield stress, and chemicals that increase temperature may be added. Such chemicals could also be beneficial for any downstream anaerobic digestion process. An example is the addition of an alkali to achieve a thermal alkaline hydrolysis. The exotherm reaction resulting
15 from the addition of lime or caustic (or any other chemical causing and exotherm reaction) would be followed by a temperature increase. In general such a temperature increase would benefit the downstream thermal hydrolysis with regards to lowering the steam consumption. In addition, the increased temperature would reduce the apparent viscosity, e.g. static yield stress and/or dynamic yield stress, of the substrate. Any
20 chemical causing an exotherm reaction needs to be followed and monitored thoroughly in order to avoid undesired events such as overheating as well as direct exposure of chemicals on the elastomers used in the stator. As a minimum, temperature and apparent viscosity, e.g. static yield stress and/or dynamic yield stress, should be monitored.

- 25 Also enzymes reducing apparent viscosity, e.g. static yield stress and/or dynamic yield stress, may be added in order to further enlarge the operational window for thermal hydrolysis on a specific substrate. The relevant type of enzymes will depend on the specific substrate, and the pre-heating and pre-conditioning device should be
30 designed to ensure sufficient mixing of the added enzymes into the substrate.

- As would be well-known by the skilled person certain sludge qualities reaches a very high apparent viscosity, e.g. static yield stress and/or dynamic yield stress, at high dry solids and becomes very difficult to transfer from the dewatering step to downstream
35 processing steps. One possibility currently used in the industry, to achieve this, is to install large pumps to produce a pressure required to pump a certain distance. However, if apparent viscosity, e.g. static yield stress and/or dynamic yield stress, is

very high, it becomes practically impossible to pump such fluids, and a common practice to overcome these problems, has up to now been to lubricate the fluid with polymer, water and even compressed air. The polymer dosing is then e.g. controlled by the pressure drop measured in on the feed line. As an example if e.g. a 13 bar
5 pressure drop was recorded for a 17 m long DN150 line, one would currently add polymer in order to overcome the high pressure which would otherwise be challenging for the installed pulper feed pumps. With this kind of lubrication, the pulper feed line can be operated with a 7-9 bar pressure drop. Under current practice in the industry, lubrication would be located directly downstream the pump located downstream
10 dewatering. In methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention lubrication would be located at a distance of up 2-10 meters downstream the pump located downstream dewatering, and this distance would be used to measure the apparent viscosity, e.g. static yield stress and/or dynamic yield stress, of the dewatered substrate in terms of the pressure
15 drop without polymer. With current technology, this information would then be used for determining the need for dilution water to adjust the DS% of the substrate. However, as will be described in the following an even more desirable way to overcome the difficulties with high apparent viscosity, e.g. static yield stress and/or dynamic yield stress, associated with cold sludge (or other substrates) at high dry solids
20 concentration, is provided by the methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention.

Thus, through research, the inventors of the methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention,
25 have found that 1) apparent viscosity, e.g. static yield stress and/or dynamic yield stress, with consequential head loss in a pipe section is almost independent of the flow rate and mostly dependent on pipe dimension, and that 2) apparent viscosity, e.g. static yield stress and/or dynamic yield stress, with consequential head loss in a pipe section is significantly dependent on temperature.

30 These surprising conclusions paves the way for a change in the way how THP feed lines are designed, and the methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention takes advantage of these two findings.

35 Even if similar behaviour has previously been demonstrated for other fluids, the clear relation found by the present inventors have not previously been disclosed for sludge

and similar substrates that are processed through thermal hydrolysis, e.g. prior to fermentation. Moreover, the present inventors have found that, because of its inherent characteristics, the thermal hydrolysis process provides an especially well-suited opportunity for utilizing these findings, i.e. as regards the apparent viscosity, e.g. static yield stress and/or dynamic yield stress, properties of sludge and similar substrates, for optimization.

As a result of this, in one embodiment, of the methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention, the pulper circulation is circulated via the pre-conditioner to increase the temperature in the mix that is returned to the pulper. Hence a common misunderstanding in the industry up till now has been that an increased flowrate, equivalent with 2-5x the THP flow rate, would increase the pressure drop in the pulper feed line. In fact the opposite takes place, as the pressure drop in the pulper feedline will drop as a result of the increased temperature rather than increase as a result of the increased flowrate.

EXAMPLES

Example 1

Figure 3 illustrates the calculated pressure drop (head loss) in a pulper feed line as a function of the flow rate. The calculation is based on sludge rheology data measured in the pulper feed line at two different plants. The two different plants produce a sludge quality with similar rheology behaviour provided that the sludge is at the same temperature. However, at different temperatures, the measured head loss in one plant becomes much lower than what is the case at the other plant. Data acquired from these two plants are basis for the calculation of head loss for a specific pipe geometry and dimension. The calculation is made for a pulper feed pipe length of 45 meter and diameter DN250mm. As can be observed in figure 3, the pressure drop may in some cases be almost independent of the flowrate, for this type of sludge with a non-Newtonian behaviour, within the flow range of 0-18m³/h. The main parameters for influencing pressure drop for a certain sludge quality is pipe diameter and rheology characteristics. Additionally, rheology characteristics is again significantly influenced by temperature. The sludge with the lowest calculated head loss in figure 3 has been preheated to 80°C, while the sludge with the highest calculated head loss is cold sludge at 20°C. This observation led to the conclusion that returning a flow of hot sludge from the pulper to upstream of the pre-conditioning mixer will significantly impact the head loss in the pulper feed pipe due to the higher temperature in the pulper feed line. The increased flowrate in the pulper feed pipe due the recycled return

flow will, however, according to Figure 3, not have much impact on the total head loss for high apparent viscosity sludge with a non-Newtonian behaviour.

Sludge is assumed to behave according to the Herschel–Bulkley model, the Bingham Plastic model, the Bingham pseudoplastic model or the Ostwald–de Waele model or similar for non-Newtonian fluids. In the Herschel–Bulkley, the Bingham Plastic, the Bingham pseudoplastic or the Ostwald–de Waele equation applied on sludge like substrates, the yield shear stress is large compared to the other parameters. This explains that for given pipe geometry, the pressure drop is almost constant and independent of flow rate within the range calculated in Figure 3. This also explains that pipe diameter has the major impact on the head loss for a certain pipe length.

Example 2

Figure 4 is based on data for two different sludge qualities and pipe configurations at approx. 20-25°C. Both data sets are re-calculated for the same pipe configuration for a Herschel–Bulkley, a Bingham Plastic, a Bingham pseudoplastic or a Ostwald–de Waele non-Newtonian fluid and also confirms the importance of pipe size in order to achieve an acceptable head loss.

Example 3

The specific selection of pump has large impact on the parameters of the methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention. In case the pressure drop in the pulper feed line can be kept as low as below 6-8bar, the pulper feed pump can be e.g. a 2 stage pump rather than a much more expensive 4 stage pump. In this embodiment of the invention, specially designed stators with mechanical anchoring should be used because of the elevated temperature and the presence of elevated levels of organic acids and other components that may harm the stator. In this embodiment of the invention the mixing of hot substrate returned from the pulper is done in the mixing zone of the pre-conditioner. In case the recycled flow of hot substrate from the pulper is larger than the cold sludge feed flow, e.g. 3X the THP feed flow, the average temperature will be sufficiently high to allow for the extruder to be removed. This embodiment of the invention is particularly suitable for inhomogeneous substrates with fibers etc that may block extruders. In case the recycled flow has a temperature of 90°C and this is mixed with cold substrate at 15°C in a proportion of 1:3, the average temperature of the mixture will be 71,2°C.

Figure 5 illustrates the average temperature of the mixture as a function of return flow temperature.

Figure 6 illustrates the average temperature of the mixture as function of return flow ratio. Return flow ratio is the ratio between the return flow at high temperature (90 C) and the feed flow at low temperature (20 C).

A consequence of the increased temperature apparent viscosity will be reduced in the pulper feed line. The decreased apparent viscosity will reduce the friction losses associated with pumping substrate to the pulper. By returning preheated substrate and mixing it into the cold substrate, the mixed substrate can more easily be pumped at a low pressure drop to the pulper.

Example 4

The ability to operate THP plants at high dry solid concentration is essential in order to hydrolyse high viscous substrates at a minimum of heat consumption. The higher energy cost are, the more important it is to be able to operate at high dry solids concentration. The higher dry solids concentration a THP plant allows for, the lower the specific steam consumption will be.

Several problems, however, arise when hydrolysing substrate at high apparent viscosity. There is a high risk of a high pressure drop in the pipelines. There is a high risk of a high power consumption during pumping. There is a high risk of a short life time of pump wear parts. There is a high risk of heat loss in the pulper and reactor due to steam tunnelling in high viscous substrates.

Various strategies have been applied to mitigate these problems in order to be able to operate thermal hydrolysis processes at high dry solids. Another challenge, however, is to know what dry solids is optimum in order to minimize steam consumption and at the same time achieve both full heat recovery as well as full and evenly distributed temperature required for the thermal hydrolysis process. Instead of trying to identify optimal dry solids content, the methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention rely on monitoring the apparent viscosity of the biomass material that is being processed and the use of these data for controlling preheating, dilution and the mix ratio between substrates. In addition the overall performance of the THP process and any

downstream process is monitored, and compliance is confirmed in a monitoring program.

A solution aimed enable high dry solids operation of thermal hydrolysis processes known from the prior art is a dynamic mixer. However, this solution only partly solves the problem and does not address the problems associated with heat recovery and operation of high viscous substrates at low temperature. Furthermore, a dynamic mixer requires increased power consumption, which is not beneficial for the overall energy consumption and operational costs. It also introduces an additional and unnecessary piece of rotating equipment that requires maintenance and represents an additional source of failures and mal-function followed by down-time of a THP plant.

A more cost efficient and far better solution would be to ensure that the above listed problems are fully addressed and solved inside the preheating tank (pulper) without adding additional rotating devices outside the pulper.

The methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention, in one embodiment describes such a solution in the form of a pre-heating tank (pulper) that utilizes the heat distribution throughout the pulper in such a way that fully preheated substrate is always pumped into the downstream THP reactors. In this embodiment the methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention also ensure a well-mixed tank (pulper), which avoids that lumps of substrate or collection of incompletely heated substrate is conveyed further into the THP train, i.e. the reactor(s) for thermal hydrolysis. This is absolutely essential for efficient operation, since such an incompletely mixed and pre-conditioned substrate would, in case of high apparent viscosity, not be fully heated and hydrolysed in the downstream reactors.

The monitoring of apparent viscosity, e.g. static yield stress and/or dynamic yield stress, will, in the methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention, be done in several stages throughout the process:

- In the pulper feed line, measuring pressure drop on a known feed pipe dimension, length and geometry.
- In the pulper circulation line and/or in reactor feed line by measuring pressure drop on a known feed pipe dimension, length and geometry.

At these positions, pressure drop, temperature, torque of pumps and flowrate are monitored continuously in the methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention.

5

In the methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention, the control points to verify a well functioning process are e.g.

- Monitoring the temperature and pressure in the pulper head space, which would
- 10 indicate tunnelling in the pulper and should, hence influence dilution rate.
- Monitoring the temperature and pressure in the reactor head space.
- Monitoring temperature fluctuations in any pulper liquid being re-circulated to the pulper or being transferred to downstream reactor(s). In case the expected
- temperature (theoretically calculated based on the pulper feed temperature and the
- 15 reactor pressure/temperature) is not reached on average at the control point, this indicates insufficient heat recovery.

In the methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention the apparent viscosity, e.g. static

20 yield stress and/or dynamic yield stress, measured and the data from the control points is utilized to control pre-heating and dilution in one or two steps:

- 1) pulper pre-heating and pre-conditioning devise, and
- 2) pulper circulation / reactor feed system.

25 Optionally the apparent viscosity, e.g. static yield stress and/or dynamic yield stress, measured and the data from the control points may also be utilized to control the operation of upstream dewatering process.

Optionally the apparent viscosity, e.g. static yield stress and/or dynamic yield stress, of

30 the hydrolysed sludge may also be measured, and this may be used to control dilution of the digester feed based on the apparent viscosity, e.g. static yield stress and/or dynamic yield stress, of the hydrolysed biomass material and the process may be verified through digester monitoring.

35 The methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention rest on the discovery that both pre-heating and dilution rate influences apparent viscosity, e.g. static yield stress and/or dynamic

yield stress, and both factors are important in order to be able to control a THP system fully as a function of the apparent viscosity, e.g. static yield stress and/or dynamic yield stress, of the processed biomass material instead of a function of dry solids content. In contrast, the prior art teaches that it is the dry solids content that needs to be both

5 monitored and controlled. In order to understand the impact of controlling the thermal hydrolysis process based on apparent viscosity, e.g. static yield stress and/or dynamic yield stress, rather than dry solids concentration, it is important to realize that different substrates may have very differing viscosities. The difference in apparent viscosity, e.g. static yield stress and/or dynamic yield stress, of two substrates at the same dry

10 solids content (DS%) and temperature could be as much as 1:500 and in some cases even more. By always optimizing the operation on basis of inline apparent viscosity, e.g. static yield stress and/or dynamic yield stress, measurements the thermal hydrolysis process can handle both varying apparent viscosity, e.g. static yield stress and/or dynamic yield stress (e.g. due to varying substrate mixtures), and varying

15 temperatures in incoming substrates without facing operational problems and without adding the unreasonable safety margin, which has been used in the prior art processes based on dry solids concentration. One example could be in co-digestion plants, treating combination of domestic sludge and import substrates. Two different substrates could have totally different rheology behaviours e.g. waste activated sludge

20 and biowaste substrate. Hence, the volume and mass ratio between two substrates could potentially vary significantly, and the optimum dry solids content for a given substrate would be unknown without significant effort. The methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention makes it possible to optimize the feed mix and the amount of dilution water

25 added in order to maximize the THP throughput at lowest possible energy consumption.

Examples of this would be:

An increase of dry solids content from 16,5% to 21% would reduce both specific

30 energy consumption and hydraulic throughput with approximately 21%.

An increase of dry solids content from 16,5% to 25% would reduce both specific energy consumption and hydraulic throughput with approximately 34%.

Thus, the methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention can through reduced energy

35 consumption improve the carbon footprint during operation.

The prior art processes have for almost all substrates, as a precaution, and in order to always be 100% certain that the thermal hydrolysis process will work well with full heat recovery rate, been run at dry solids content of average 16,5% and maximum 18,0% by default. The methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention enables a differentiation of dry solids content based on the discovery that the actual limiting factor for a THP process, apparent viscosity, e.g. static yield stress and/or dynamic yield stress, is continuously monitored and optimized through:

- 1) Optimized pre-mixing of substrates
- 10 and/or
- 2) optimized injection rate and mixing of dilution water into the substrate
- and/or
- 3) optimized injection rate and mixing of pre-heated dilution water into the substrate
- 15 and/or
- 4) optimized injection rate and mixing of chemicals into the substrate
- and/or
- 5) optimized injection rate and mixing of enzymes into the substrate
- and/or
- 20 6) optimized upstream dewatering of the substrate
- and/or
- 7) optimized return flow from the pulper to the pre-conditioner to reduce pressure drop in pulper feed line.

25 Either of the above measures is followed by a monitoring of temperature profile inside the device and/or the THP feed pipe, which is used as an indicator of how successful the pre-conditioning device has been on mixing the substrate(s). Statistical analysis is used to indicate the stability of the process.

30 In one embodiment of the methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention a particular beneficial pulper design is used in which:

In this particular beneficial pulper design the total pulper volume vs the average
35 reactor filling volume is in the range of 2.1 and 3.0.

In addition, in this particular beneficial pulper design, the pulper outlet nozzle connected to the reactor feed pump is at an elevated level in order to ensure that pre-heated substrate will be extracted from the pulper and avoid that insufficient heated sludge and cold sludge is extracted from the bottom of the vessel.

5

Furthermore, in this particular beneficial pulper design, the volume below the outlet nozzle for the pump(s) is ≥ 1.6 times the average reactor filling volume. The volume above the nozzle is >1 times the average reactor filling volume. The head space volume at maximum fill rate should be at least 10%, preferably $>20\%$ of the total

10 volume or more favourable 20-30% of total volume. This will allow for splashing and foaming incidents without causing operational problems. The plant may operate typically at 70-80% fill rate as a target, while the actual volume will vary depending on the average reactor feed rate.

15 Sludge and similar substrates have a non-Newtonian behaviour. For such substrates, pipe dimension is important for pressure drop, even at low flowrate. High pressure drop on suction side of pumps is not beneficial for pumps operating on liquids near the boiling point as it may cause cavitation and operational challenges for the pumps. The dimension of the pulper outlet nozzle, in the particular beneficial pulper design of the
20 present invention, is preferably be $\geq \text{DN}200$ to handle high viscous substrates, and the length of the suction pipe between the nozzle and the pump does preferably not exceed 4m. For smaller dimension pipe, e.g. DN150, the length of the pipe should be reduced to ensure low pressure loss through the pipe.

25 The sludge entering a pulper vessel is colder than the sludge inside the pulper. As a consequence of this temperature difference, the cold feed sludge has a higher apparent viscosity, e.g. static yield stress and/or dynamic yield stress, than the warmer sludge inside the pulper. In the particular beneficial pulper design of the present invention, the cold feed sludge is added into the hot sludge via a sludge distributor in
30 the upper part of the pulper in order to distribute the cold sludge entering the vessel into the pre-heated sludge. Preferably, the distribution device should be located in the headspace preferably above liquid level. Preferably the sludge distributor will be in the form of an extruder consisting of a pipe with many holes where the sludge is distributed and sliced into smaller parts and thus create a larger surface area.

35 Preferably the total area of the holes in the extruder should be $>2,5$ times the cross section of the feed pipe(s) to the extruder to avoid undesirable pressure loss across the extruder. The dimension of the holes in the extruder should be between 10mm and

50mm, preferably between 18 and 35mm, most preferably 20-30mm. The smaller the holes, the better distribution, however, substrate includes fiber, textiles, plastic, hair and other particles that tend to block an extruder with too small holes. For most substrates an extruder with 25mm holes will suffice. The extruder may also have oval
5 holes, slits or any other shapes that ensures an efficient distribution of substrate in the top section of the pulper. Other distribution systems may also be used, such as screw, spreader stoker, dices or any other system that distribute the incoming sludge into smaller particles that provides an extended heat surface to transfer heat from the preheated sludge inside the pulper. Sludge entry into the tank, should not be located
10 straight above the outlet nozzle. Short horizontal distance between inlet nozzle and outlet nozzle will cause short-circuiting. The inlet of sludge, preferably through and extruder, should be located at the opposite side of the pulper. In practicality, for a vertical standing pulper with outlet on the side of the pulper, the inlet extruder should be located horizontally and diagonally 90° away from the outlet nozzle, and not closer
15 to the outlet nozzle than diagonally in centre of the vessel, preferably off set center away from the outlet nozzle. The particular beneficial pulper design according to the present invention may also be horizontal, and in also in such cases, the extruder should be located in a far distance away from the outlet nozzle. This can be achieved by different orientations and location of the extruder.

20

In one embodiment of the particular beneficial pulper design according to the present invention, parts of the extruder is blocked in order to 1) increase distance to the outlet nozzle of the pulper, and 2) avoid splashing into other nozzles located in the headspace of the pulper.

25

It is beneficial, in the particular beneficial pulper design according to the present invention, to recirculate sludge through the extruder. This recirculation may also include a partial or full flow back to the pre-conditioner in order to improve premixing as well as reduce pressure drop in pulper feedline. Preferably this recirculation loop is
30 capable of recycling an amount of preheated biomass material from the pulper equivalent to at least 0.5 times the amount of cold biomass material feed, preferable more than 1 times the cold biomass material feed, and even more preferably more than 2 times the cold biomass material feed.

35 It is also beneficial, in the particular beneficial pulper design according to the present invention, to recirculate sludge to the bottom of the pulper.

In a 1. Alternative of a particular beneficial pulper design according to the present invention apparent viscosity, e.g. static yield stress and/or dynamic yield stress, is measured in a circulation loop on the pre-heating pulper that includes a pump that produces a controlled flowrate, preferably a progressive cavity pump, a pipe section
5 with a known geometry restricting the flow. The apparent viscosity, e.g. static yield stress and/or dynamic yield stress, is then measured in terms of pressure drop at a known flowrate through the known pipe geometry.

In a 2. Alternative of a particular beneficial pulper design according to the present
10 invention the apparent viscosity, e.g. static yield stress and/or dynamic yield stress, is measured in the reactor feed line. The reactor feed line includes a pump function capable of producing a controlled flowrate, a pipe section with a known geometry restricting the flow. The apparent viscosity, e.g. static yield stress and/or dynamic yield stress, is then measured in terms of pressure drop at a known flowrate through the
15 known pipe geometry.

Pump function in a particular beneficial pulper design according to the present invention can be fulfilled in several different ways, e.g. progressive cavity pump, centrifugal pump, piston pump, barometric egg, or any other way of controlling the
20 flowrate.

A flowmeter can be used to verify flowrate, or control flow through the system.

A pressure sensor can be used to measure pressure drop.
25

The above-described system(s) to measure apparent viscosity, e.g. static yield stress and/or dynamic yield stress, for a particular beneficial pulper design according to the present invention will not suffer from operational problems that can be challenging in standard apparent viscosity, e.g. static yield stress and/or dynamic yield stress,
30 measurement instruments on inhomogeneous substrates such as sludge and biowaste that contain components that tend to block and clog narrow passes.

Similar benefits and performance as for the above-described embodiment of a particular beneficial pulper design according to the present invention can be achieved
35 by alternative means. Hence, another embodiment of the invention would be to establish an overflow vessel, or compartment of a vessel that is essentially always filled. When adding more cold sludge into the overflow vessel, or compartment of a

vessel, heated sludge would flow to the next vessel or compartment that is used as a chamber for pumping the material into the downstream reactors. This embodiment of the invention would in the same way as the previously described embodiment of the invention utilize the temperature stratification that takes place in the pulper, and
5 always skim off the warmest sludge. The pumping of heated substrate from the pulper to the reactor vessels may take place by conventional pumps e.g. progressive cavity pumps, centrifugal pumps or any other pump type. The pumping could also take place by pressurizing the pulper vessel compartments in order to push the substrate to downstream reactors.

10

An essential problem with extruder design is that insufficient screening of sludge may cause blocking of the extruder. Cleaning of extruders installed in the head space of pulpers is difficult and time consuming. Thus, a particular preferred embodiment of a particular beneficial pulper design according to the present invention includes an
15 alternative design of the extruder, in which the extruder is located outside the pulper vessel. The extruder can thus be isolated and cleaned on regular basis without interfering with the pre-heating vessel (pulper) itself. During cleaning of the extruder, the extruder may be by-passed, or the system is equipped with duty standby extruders to ensure that one extruder will always be in operation.

20

It is also foreseen that some substrates that are not well screened upstream the process would benefit from continuous cleaning. Hence, in a particularly preferred embodiment, the extruder design may also include a self-cleaning function.

25 Even if the above-mentioned embodiments are preferred, the methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention are able to utilize any type of extruder or filter that cuts the cold substrate into smaller pieces, where the smaller pieces with a larger specific surface area is blended into the warmer substrate. The extruder or filter applied should provide
30 preferably >10x larger specific surface area of the cold substrate by distributing the supplied cold substrate into smaller parts. The extruded or filtered substrate with a larger specific surface area is mixed into a larger amount of preheated substrate that is circulated from the preheating tank (pulper). The amount of circulated pre-heated substrate should be at least >3x the amount of cold substrate feed to the system.

35

The extruder may also be implemented in form of a screw press to enable continuous removal of grit, fiber, plastic, textiles etc.

A possible design of a particular beneficial pulper design of the methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention including an extruder, is shown in Figure 7.

5

The extruder could also be prepared for injection and more efficient mixing of chemicals as the sludge, once preheated, has a significant lower apparent viscosity than when not preheated.

- 10 Up to now the current trend in the industry has been to invest in expensive DS%-meters. However, these instruments are not always reliable on substrates at high apparent viscosity and varying apparent viscosity, and it is a problem that the signals tend to drift. Instead the methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention rely on soft sensors
- 15 based on simple and reliable information acquired from the system with a minimum of instrumentation installed. As the real limitation for the thermal hydrolysis process is the apparent viscosity, e.g. static yield stress and/or dynamic yield stress, it makes much more sense to measure the apparent viscosity, e.g. static yield stress and/or dynamic yield stress, rather than DS% and implement dilution based on apparent viscosity, e.g.
- 20 static yield stress and/or dynamic yield stress, only.

Apparent viscosity, e.g. static yield stress and/or dynamic yield stress, measurement in the pulper feed line can be achieved by installing Pressure transmitters right after the pulper feed pump and after some meters of pipe, preferably prior to the pulper inlet.

- 25 Pressure drop is measured on the pipe section and dilution and preheating is based on the measured pressure drop.

- Apparent viscosity, e.g. static yield stress and/or dynamic yield stress, measurement in the pulper feed line can also be achieved by installing temperature transmitter on the
- 30 pulper feed line to have a reference for determining the apparent viscosity, e.g. static yield stress and/or dynamic yield stress. Flowmeters are more difficult and inaccurate due to the low flowrate and the fact that small cross sections in flow transmitters is not preferred as it will cause additional pressure drop.

- 35 Apparent viscosity, e.g. static yield stress and/or dynamic yield stress, measurement in the Pulper circulation line can be achieved by:
- Installing a temperature transmitter,

- Installing 2 pressure transmitters, with some distance between, prior to the extruder in order to avoid disturbances from the extruder in case the extruder is gradually blocking.
- Injecting preheated dilution water into the pulper circulation pumps in case of high pressure drop in the pipeline.
- Increase dilution rate upstream into the pre-conditioner in case of high temperature fluctuations in the pulper indicating too high apparent viscosity, e.g. static yield stress and/or dynamic yield stress.

10 Apparent viscosity, e.g. static yield stress and/or dynamic yield stress, measurement in the Reactor feed line can be achieved by:

- Installing temperature transmitter
- Installing pressure transmitter
- Installing flow meter
- Measuring the pressure drop between the pressure transmitter and any pressure transmitter(s) in the reactor(s).

20 Apparent viscosity, e.g. static yield stress and/or dynamic yield stress, measurement in the Reactor feed line can be achieved by using the torque or power consumption available on the pump frequency converter.

Apparent viscosity, e.g. static yield stress and/or dynamic yield stress, measurement in the Pre-cooler can be achieved by:

- Installing temperature transmitters
- Installing flow meter
- Installing pressure transmitter on precooling circulation line.
- Measuring the pressure drop between the pressure transmitters.

30 Apparent viscosity, e.g. static yield stress and/or dynamic yield stress, measurement in the Digester feed line can be achieved by:

- Installing temperature transmitter
- Installing pressure transmitter at digester feed pump and prior to interface to the digester feed line.
- Installing flow meter
- Measure pressure drop between pressure transmitters.

Figure 8 shows embodiments of the present invention including a particular beneficial pulper design according to the present invention.

Figure 9 shows a preferred sludge extruder in a particular beneficial pulper design
5 according to the present invention.

Figure 10A shows data from a case study in relation to performance data of a pulper modification upgrade, involving the upgrade from a prior art design to a particular beneficial pulper design according to the present invention. As can be seen the ability
10 of the pulper according to the present invention to keep the temperature of the material discharged from the pulper within certain limits is dramatically improved compared to that of the prior art. Hence, a pulper according to the present invention (16 hour trends) makes it possible to keep the temperature of the material discharged from the pulper within a temperature span of app. 20 C (i.e. varying from app. 65 C to app. 85
15 C), whereas the temperature span enabled by the pulper of the prior art (8 hour trends) is almost twice as large, i.e. 40 C (vis. From app. 45 C to app. 85 C).

Figure 10B shows the standard deviation of reactor feed temperature for individual reactor fillings in a method according to the present invention, employing a pulper
20 according to the present invention calculated based on temperature measurement every 5 seconds. As can be seen it is ensured that pre-heated biomass material produced in a pulper from a non-Newtonian biomass material and to be subsequently fed to any downstream thermal hydrolysis reactor of a THP system, and/or subsequently from the THP system to any subsequent processing steps, is of a
25 uniform temperature, i.e. such that the average standard variation in temperature is $<12^{\circ}\text{C}$, when this standard variation in temperature is calculated based on a temperature measurement resolution of < 5 seconds, and used to calculate an overall average for each individual reactor filling.

Figure 11 shows data from a case study in relation to performance data of a pulper modification upgrade, involving the upgrade from a prior art design to a particular beneficial pulper design according to the present invention (i.e. with and without upgrade kit). As can be seen the ability of the pulper according to the present invention to provide reactor feed flows of above $30 \text{ m}^3/\text{h}$ at even very high dry matter content is
30 dramatically improved compared to that of the prior art. Hence, a pulper according to the present invention makes it possible to work reactor feed flows of above $30 \text{ m}^3/\text{h}$
35

when working with material having a DS well-above 14%, which is not possible with a pulper of the prior art.

Example 5

- 5 Figure 12 is based on data from operation at selected dry solids content from 16% to 18%DS, during development and testing of the particularly beneficial pulper design according to the present invention described in example 4, and shows the relationship between τ_o and WAS%. As can be seen it was shown that WAS% up to 100% can be achieved at dry solids content up to 18%.

10

As can be seen from figure 12, the particularly beneficial pulper design according to the present invention described in example 4 can tolerate an apparent viscosity indicative of a static yield stress of up to $\tau_o = \sim 1700-2200$.

- 15 Figures 13A and B demonstrate that the particularly beneficial pulper design according to the present invention described in example 4 can operate stably at an apparent viscosity indicative of a static yield stress of $\tau_o = 1500-2000$ Pa on 100% WAS. In case of 30% WAS and 70% primary sludge, the apparent viscosity at the same conditions (DS% and temperature) is indicative of a static yield stress of approximately $\tau_o = 500 -$
20 1000 Pa. In case a plant is operated on 30%WAS and 70% primary sludge, the dry solids content could be increased until the apparent viscosity reaches a level indicative of a static yield stress of $\tau_o = 1700-2200$ Pa. In this case the dry solids content can be increased from 16-18%DS and up to 20-22%DS, and in some cases further increased up to 25%DS or more for some substrates or mixes of substrates. Such an increase
25 would cause a reduced specific steam consumption of 20% and 38% respectively. An additional benefit is that the hydraulic capacity can be maintained at high dry solids operation. As a consequence, the dry solids capacity can also be increased with 20% and 38% respectively.

30 Example 6

- When applying apparent viscosity, e.g. static yield stress and/or dynamic yield stress, as a parameter to control dilution rate in order to optimise the THP process, there is a risk that dry solids content (DS%) of digester feed will vary without being in control of the actual VS feed rate. However, Even more important than VS feed rate is the actual
35 energy feed rate. Different sludge qualities and other substrate qualities have different specific energy content. One way to measure specific energy content is to measure COD/VS as this explains the energy density of the volatile solids that is present in the

substrate. A further background for the methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention is the discovery of the present inventors of the relationship between specific energy content, measured as COD/VS and rheology, measured as τ_o .

5

Figure 14 demonstrates this relationship.

The relationship between specific energy content, measured as COD/VS and rheology, measured as τ_o (Figure 14) has been developed based on the relationship
10 between τ_o and WAS/Primary sludge ratio as shown in Figure 15.

Furthermore, the calculated function of τ_o as $f(\text{COD/VS})$, which is visualised in Figure 14, is based on energy content in Primary sludge of 1,7 and in Waste Activated sludge of 1,45. Variations in energy content can be expected depending on sludge origin,
15 sludge age, etc, and a calibration is recommended for each sludge mix. The validity of the identified relationship that can be used to determine energy content in sludge and thus be used to control energy feed rate to digesters is predominantly for $\tau_o > 500 - 1000 \text{ Pa}$ and $\text{COD/VS} > 1,52$ depending on type of substrate.

20 Specific COD/VS for each category of sludge and substrate will vary, depending on upstream waste water treatment process, waste water quality, sludge age, etc. The correct mathematical relation will thus vary. However, a similar relation would be expected to be found for many substrates, and this can then be calibrated based on sampling of actual substrates that will be mixed.

25

One way of controlling the validity of a calibrated system and to determine the need for closer monitoring and possible recalibration is, in addition to regular sampling for analysis of COD/VS, to also analyse for organic Nitrogen content. Different sludge and substrates have different organic nitrogen content. Typically, primary sludge has an
30 organic nitrogen content of around 2,5% of the VS content, while Waste activated sludge (WAS) typically has an organic nitrogen content of around 6,0%. An indirect way of controlling the energy content is thus to analyse for the organic nitrogen content of the sludge. The relationship between τ_o and organic nitrogen content in sludge can be calculated as shown in Figure 16. Also this relationship will vary,
35 depending on the waste water treatment process, waste water quality, how the process is operated, sludge age, etc.

Once the relation has been established and calibrated the methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention enable τ_0 to be used for predicting organic nitrogen concentration in the sludge mix and thus the organic nitrogen load to the digester.

5

An important reason for applying thermal hydrolysis prior to anaerobic digestions is that the sludge behaviour is radically changed so that the sludge becomes easier digestable. The hydrolysis step takes place prior to the remaining anaerobic digestion process and the digestion process goes thus much faster. Matt Higgins (2021, Bucknell University, Lewisburg, Pennsylvania) demonstrated that mixed sludge can be well digested in a one stage digestion process within 10 days HRT without significantly reduction in methane yield, VS destruction and dewaterability. Acceptable results could be achieved also at 8 days HRT, while the performance would quickly decrease at 6 days HRT. Going to such short retention times by applying thermal hydrolysis would increase the capacity, throughput and utilization of existing digestion plants significantly. Furthermore, new anaerobic digestions plants could be build at significantly reduced cost just like it would reduce the environmental footprint and the area required equivalently. This would also benefit the overall carbon footprint compared to conventional anaerobic digestion without thermal hydrolysis.

20

When operating anaerobic digestion processes at such high loading rate (7-8 kgVS/m³d) and short retention time (10 days), the process may suffer quickly from further rapid increase in feed rate. The methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention introduces apparent viscosity, e.g. static yield stress and/or dynamic yield stress, as a steering parameter for running the thermal hydrolysis process at maximum possible dry solids content in order to reduce the specific heat consumption without achieving operational challenges in the pretreatment process upstream the anaerobic digestion process. In case changes in the feed mix reduces the apparent viscosity, e.g. static yield stress and/or dynamic yield stress, e.g. through changed primary/secondary sludge ratio, the methods, systems, process equipment and plants employing Thermal Hydrolysis Processes (THP) of the present invention enable an automatic increase in DS% through a reduced dilution rate or an increased DS% from pre-dewatering. A way to further improve digester loading rate, is by predicting both DS%, VS% and COD/VS (energy density) as well as organic Nitrogen content based on measurements of the rheological behaviour of the biomass material throughout the THP process. In addition

35

digester control can be further improved by monitoring key performance indicators in the anaerobic digestion process.

Key Performance Indicators (KPI) that can be monitored in the anaerobic digestion

5 process to improve control include:

pH

CH₄ concentration

Biogas production rate

FOS/TAC

10 Specific biogas yield pr kg DS (Nm³/kgDS)

Specific methane yield pr kg VS (Nm³/kgVS)

Digester loading rate (kgVS/m³d)

Data to be logged in order to identify these KPI's on a continuous basis include:

15 pH

CH₄ concentration

Biogas flow

Digester feed flow

Digester DS% aquired from the apparent viscosity, e.g. static yield stress and/or

20 dynamic yield stress

Digester VS% aquired from the apparent viscosity, e.g. static yield stress and/or

dynamic yield stress

DS% and VS% should be sampled and analysed continuously in order to calibrate the

25 relation between apparent viscosity, e.g. static yield stress and/or dynamic yield

stress, and DS% and between apparent viscosity, e.g. static yield stress and/or

dynamic yield stress, and VS%. This should be done both in the digester feed line and

in the pulper circulation/reactor feed line.

CLAIMS

1. Method for treating a non-Newtonian biomass material having:

- a dry-matter content (DS%) of at least 12%,
- 5 - a ratio between the chemical oxygen demand (COD) and volatile solids content (VS), COD/VS-ratio, of less than 2.0, and
- a static yield stress, τ_o , of between 150 and 2500 Pa, such as above 200, such as above 250 Pa, such as above 300 Pa, such as above 350 Pa, such as above 400 Pa, such as above 500 Pa, such as below 2400
- 10 Pa, such as below 2200 Pa, such as below 2000 Pa, such as below 1800 Pa, such as below 1600 Pa, such as between 300 and 1700 Pa, such as between 400 and 1700 Pa, such as between 500 and 1700 Pa, such as between 600 and 1700 Pa and/or a dynamic yield stress, τ_y , of between 50 and 500, such as above 100, such as above 150 Pa, such as above
- 15 200 Pa, such as below 450 Pa, such as below 400 Pa, such as below 350 Pa, such as below 300 Pa, such as below 250 Pa, such as between 50 and 400 Pa, such as between 50 and 300 Pa

said method comprising the steps of:

- a) feeding said non-Newtonian biomass material to one or more pulpers
- 20 by one or more pulper feed lines at a controlled DS% and/or COD loading rate,
- b) homogenizing and pre-heating said non-Newtonian biomass material in said one or more pulpers resulting in a pre-heated biomass material,
- c) discharging said pre-heated biomass material from said one or more
- 25 pulpers,
- d) feeding said pre-heated biomass material to a thermal hydrolysis system, operated at a higher temperature than the temperature of said pre-heated biomass material, by one or more feed lines at a controlled DS% and/or COD loading rate,
- 30 e) thermally hydrolysing said pre-heated biomass material in said thermal hydrolysis system resulting in a hydrolysed biomass material, and
- f) subsequently processing at least part of said hydrolysed biomass material in one or more subsequent processing systems by transferring said hydrolysed biomass material to said one or more subsequent
- 35 processing systems, by one or more feed lines at a controlled DS% and/or COD loading rate,

wherein said method is further characterized in that:

- said controlled DS% and/or COD loading rate of said non-Newtonian biomass material through said one or more pulper feed lines and pulpers of steps a) - c), and/or
- 5 - said controlled DS% and/or COD loading rate of said pre-heated biomass material through said one or more thermal hydrolysis system feed lines and said thermal hydrolysis system of steps d) and e), and/or
- said controlled DS% and/or COD loading rate of said hydrolysed biomass material through said one or more feed lines of step f),
- is controlled based on:
- 10 - continuously or semi-continuously determining the static yield stress, τ_o , and/or dynamic yield stress, τ_y , of said non-Newtonian biomass material, said pre-heated biomass material and/or said hydrolysed biomass material, by continuously or semi-continuously measuring pressure drop, temperature and flowrate in:
- 15 - said feed line(s) for said one or more pulpers of step a), and/or
- said feed line(s) for said thermal hydrolysis system of step d), and/or
- 20 - said feed line(s) for said one or more subsequent processing system of steps f), and/or
- one or more thermal hydrolysis discharge or recirculation lines of said thermal hydrolysis system of step d) and e), and/or
- 25 - one or more circulation lines of said one or more pulpers of steps a) – c),
- and
- continuously or semi-continuously measuring one or more parameters of said one or more subsequent processing systems of step f)
- thereby establishing, which controlled DS% and/or COD loading rate;
- 30 - of said non-Newtonian biomass material, at said determined static yield stress, τ_o , and/or dynamic yield stress, τ_y , through said one or more pulper feed lines and pulpers of step a); and/or
- of said pre-heated biomass material, at said determined static yield stress, τ_o , and/or dynamic yield stress, τ_y , through said thermal hydrolysis feed lines and thermal hydrolysis system of step d); and/or
- 35

- of said hydrolysed biomass material, at said determined static yield stress, τ_o , and/or dynamic yield stress, τ_y , through said feed lines for said one or more subsequent processing system of step f)
is characteristic of at least one of said one or more of parameters of said subsequent
5 processing systems of steps f).

2. A method according to claim 1, wherein said non-Newtonian biomass material displays:
- a static yield stress, τ_o , of at least 500 Pa, such as at least 1000 Pa,
10 such as at least 1500 Pa, and/or
- a dynamic yield stress, τ_y , of at least 80 Pa, such as at least 100 Pa, such as at least 120 Pa.

3. A method according to any of claims 1 or 2, wherein said thermal hydrolysis system
15 of steps d) and e) includes:
- one or more reactors working in parallel or series in which said pre-heated biomass is subjected to heating and elevated pressures, and
- one or more flashtanks to which said biomass is transferred from said one or more reactors, whereby a pressure reduction occurs in one or more stages wherefrom flash
20 steam results,
and wherein
- said pre-heating of said biomass material in said one or more pulpers of steps a) - c), which may work in parallel or series, is achieved by injection of flash steam recovered from said thermal hydrolysis system of steps d) and e).

25
4. A method according to any of claims 1 to 3, wherein said non-Newtonian biomass material has a dry-matter content (DS%) above 20% and wherein:
- at least 50% of said resulting hydrolyzed biomass material is recirculated by transport from i) downstream said hydrolysis system of steps d) and e), to ii) upstream said
30 hydrolysis system of steps d) and e), and/or
- the biomass material is pre-heated in said pulpers of steps a) to c) and thermally hydrolysed in said thermal hydrolysis system of steps d) and e) by subjecting said biomass material to multiple steps involving stepwise heating and cooling in one or more pulpers for heating, one or more reactors for treatment at a pre-
35 selected temperature of above 150°C, more preferably above 160°C, or even more preferably above 180°C, and one or more flashtanks for pressure reduction and/or cooling.

5. A method according to any of claims 1 to 3, wherein said non-Newtonian biomass material has a dry-matter content (DS%) above 20% and wherein said one or more subsequent processing systems of step f) includes:

- 5 f1) a separation step to produce at least two fractions, of which one is rich in liquid compared to said hydrolysed biomass material and one is rich in solids compared to said hydrolysed biomass material, and,
- 10 f2) transferring, by one or more feed lines, said hydrolysed biomass material, parts of, or all of, one or all of said at least two fractions produced in said separation step of step f1) to one or more processing units for anaerobic fermentation, and,
- 15 f3) transferring, by one or more feed lines, said hydrolysed biomass material, parts of, or all of, one or all of said at least two fractions produced in said separation step of step f1) to one or more processing units for thermal reduction of organic compounds,
- and wherein:
- at least part of a material resulting from said anaerobic fermentation of step f2) is at least partly dewatered and the resulting dewatered material is transferred by one or more feed lines, to said one or more processing units for thermal reduction of organic compounds of step f3).
- 20

6. A method according to any of claims 4 or 5, wherein said resulting hydrolyzed biomass material of step e) is recirculated by transport, by use of one or more mixing augers and pumps, preferably progressive cavity pumps, and preferably one or more augers with a conveying capacity of at least 1.5 times that of the pumps, from i) downstream said hydrolysis system of steps d) and e), to ii) upstream one or more of said pulpers of steps a) - c) and mixed with said non-Newtonian biomass material thereby acting to reduce the static yield stress, τ_o , and/or dynamic yield stress, τ_y , of the material fed to said pulpers
- 25
- 30

7. A method according to any of claims 1-6, wherein preheated biomass material from one or more pulpers of steps a) – c) is recirculated by transport, by use of one or more mixing augers and pumps, preferably progressive cavity pumps, and preferably one or more augers with a conveying capacity of at least 1.5 times that of the pumps, to upstream said one or more pulpers of steps a) – c) and mixed with said non-
- 35

Newtonian biomass material thereby acting to reduce the static yield stress, τ_o , and/or dynamic yield stress, τ_y , of the material fed to said pulpers.

8. A method according to any preceding claims, further characterized in that:

- 5 - heat-exchangers are employed to recover heat from the cooling of said hydrolyzed biomass material of step e) prior to said hydrolyzed biomass material being subjected to said subsequent processing in said one or more subsequent processing steps f), preferably by cooling said hydrolyzed biomass of step e) by subjecting said hydrolyzed biomass material to heat-exchange with water in a heat-exchanger, and subsequently
- 10 injecting said water into said non Newtonian biomass material of step a) said pre-heated biomass material of step b). or preheating polymer/water in upstream pre-dewatering or thickening processes.

9. A method according to any preceding claims, further characterized in that said non-

- 15 Newtonian biomass material of step a) displays:
- a static yield stress, τ_o , of above 2000 Pa, such as above 2200 Pa, such as above 2300 Pa and
 - a dynamic yield stress, τ_y , above 300 Pa, such as above 350 Pa, such as above 400 Pa,
- 20 and
- the static yield stress, τ_o , of the material fed to said pulpers is reduced to a value below 1700 Pa such as below 1500 Pa, and/or
 - the dynamic yield stress, τ_y , of the material fed to said pulpers is reduced to a value below 250 Pa, such as below 200 Pa

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10. A method according to claim 9, further characterized in that inorganic particles and/or undissolved material is continuously separated from said hydrolyzed biomass material of step e) by degritting prior to said subsequent processing of step f).

- 30 11. A method according to claim 5 where at least part of the at least one fraction of step f1) rich in liquid compared to said hydrolyzed biomass material is recirculated by transport to
- upstream one or more of said pulpers of steps a) - c) and mixed with said non-Newtonian biomass material thereby acting to reduce the static yield stress, τ_o , and/or
- 35 the dynamic yield stress, τ_y , of the material fed to said pulpers,

- upstream said hydrolysis system steps d) - e) and mixed with said pre-heated biomass material thereby acting to reduce the static yield stress, τ_o , and/or the dynamic yield stress, τ_y , of the material fed to said hydrolysis system, and/or
 - upstream said separation step f1) and mixed with said hydrolyzed biomass material
- 5 thereby acting to reduce the static yield stress, τ_o , and/or the dynamic yield stress, τ_y , of the material fed to said separation step f1).

12. A system for processing a biomass material having a dry-matter content (DS%) above 12%, said system comprising:

- 10 - a pulper for homogenizing and pre-heating said biomass material having a dry-matter content (DS%) above 12%,
- a a thermal hydrolysis reactor for subjecting said homogenized and pre-heated biomass material to thermal hydrolysis,
- said system being characterized in that:
- 15 - the total volume of said pulper is > 2.6 times and < 20 times, preferably 2.6 to 6 times, the average filling volume of said thermal hydrolysis reactor
- said pulper comprises an outlet nozzle, for discharging said pre-heated material from said pulper, which is placed in such a way that:
- 20 - the part of the total -volume of said pulper below said outlet nozzle is ≥ 1.6 times the average filling volume of said thermal hydrolysis reactor, and
- the part of the total volume of said pulper not below the outlet nozzle is > 1 times the average filling volume of the thermal hydrolysis reactor.

- 25 13. A system according to claim 12 further characterized in that said pre-heating in said pulper is at least partly achieved by injection of flash steam from a thermal hydrolysis system.

14. A system according to any of claims 12 or 13, further characterized in:

- 30 a) that:
- the part of the total volume of said pulper below said outlet nozzle, and
 - the part of the total volume of said pulper not below the outlet nozzle,
- are provided in the form of at least two separate interconnected chambers or tanks,
- 35 b) that said outlet nozzle is in the form of an overflow edge, knife or similar outlet fitted on the first of said at least two separate interconnected chambers or tanks, which ensures that a volume

- corresponding to ≥ 1.6 the average filling volume of said thermal hydrolysis reactor is continuously present below said edge, knife or similar outlet in said first of said at least two separate interconnected chambers or tanks, and
- 5 c) that said pulper includes a biomass material distributor, preferably designed as an extruder, acting to split incoming cold biomass material into smaller segments before the biomass material enters the pulper.
15. A system according to any of the preceding claims further characterized in that
- 10 said pulper includes a recirculation loop capable of recycling an amount of preheated biomass material from said pulper equivalent to at least 0.5 times, preferably more than 1 times, and even more preferably more than 2 times the amount of cold biomass material feed and mixing said preheated biomass material with cold biomass material prior to its entry into or inside said biomass material distributor.
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