Innovative Small Size Plant for the Production of Biogas and Electric Energy from Biomass

Farné Stefano

Department of Industrial, Electrical, Computer and Biomedical Engineering, University of Pavia, Italy.

Country: Italy

ABSTRACT

The interest for Renewable Energy Sources (RES) has strongly increased due to the need to reduce the greenhouse gas (GHG) emissions, as indicated, in particular, by the renewable energy directive 2018/2001/EU and to reuse organic waste and by-products that would otherwise have to be disposed of in an expensive way. The present article relates to a method and to a device to decompose a biomass matrix and to selectively extract methane, carbon dioxide, NPK (nitrogen, phosphorus and potassium) salts and clarified water. This method and device is the subject of an Italian and European patent registered by Stefano Farné and Vito Lavanga under the name of MBGC (Mini BioGas Continuous). The MBGC can be applied to the production of biomethane (for thermal and electrical purposes), of organic (protein and oleic) substances, of NPK salts, that can be used in the production of biofuels, fertilizing mixtures for various industrial sectors (livestock farms, chemical, etc.), of hydrogen, as present in solution in the liquid phase and of carbon dioxide for agronomic industries, metallurgical industries, fire services, agro-food etc. It has been analysed a meaningful literature on the subject of biogas production plants, with specific focus to those of small size and subsequently the MBGC plant is described in detail from the point of view of both plant engineering and its operation.

Keywords: Biogas, biomass, anaerobic digestion, biomethane, NPK salts.

1. Introduction

It is strongly felt the need to have systems for the reuse aimed at restoring value to limited quantities of organic matrices (sewage, manure, wet waste, wastewater etc.), often considered as organic waste to be disposed. These organic matrices can be produced by little farms, livestock, fruit and vegetable markets, mowing and pruning, grass cuttings, accommodations (hotels and residences for the elderly), restaurants, catering and residential settlements (like condominiums, small neighborhoods, villages, etc.). The costs and the inconveniences of their treatment are not negligible and they can affect a company's balance, as well as negatively impact the environment. At the same time there is a general need for the supply of energy, better if renewable, available at the production site of the waste and therefore, substantially, at "zero km". The current state of the art includes anaerobic digesters usually intended to high productions, with very high costs and generally ineffective for small power, small free space available, small quantities of organic matrices to be disposed. The digesters currently present, moreover, does not offer effective solutions for the management of digestate and of other by-products.

The development potential of biogas plants has been the subject of numerous studies. A review paper (Capodaglio et al., 2016) has analyzed the most promising emerging biogas technologies in the perspective of their potential uses, environmental benefits, and public acceptance, drawing a picture of current conditions on the adoption of a biogas road map in several EU Member States. At the national level, it has been predicted (Comparetti et al., 2013) the Sicilian potential biogas production, using the Organic Fraction of Municipal Solid Waste (OFMSW), animal manure, food industry by-products; this study was based on the statistical data about OFMSW, the number of animals bred in medium and large farms and the amounts of by-products of food processing industries. A similar study has been conducted (Valenti et al., 2017) on the potential biogas production from agricultural by-products (citrus pulp and olive pomace) in Sicily while it has been determined the potential energy production from anaerobic digestion of animal wastes and agricultural residues in Friuli Venezia Giulia (dell'Antonia et al., 2013), both finding very interesting potential. The environmental sustainability of this energy source was analyzed in

various studies (Bacenetti et al., 2013 and 2014) that have considered all the factors having environmental effects (field operations, inputs as fuels, fertilizers and pesticides, extraction, production and transportation) of maize silage and of different crop systems for biomass and biogas production. Moreover (Bacenetti et al., 2013) the environmental assessment of the production of electricity from anaerobic digestion of zootechnical waste has been studied. The use of the latter kind of sewage has been investigated (Coppolecchia et al., 2015) in three different Italian dairy farms, showing how the most common techniques (scraper, slatted floor, flushing) can change the characteristics of collected manure; this study should be taken into account in defining the input compound system in MBGC. With regard to the input compound features, a comparative study was set up (Dinuccio et al., 2013) in order to assess the technical feasibility of the long-term reuse of the mechanically separated co-digested solid fraction as a feedstock for anaerobic digestion plants. The relationship between the input compound and the biogas obtained from the anaerobic digestion has been investigated (Comparetti et al., 2013), determining the chemical composition of kitchen waste and cheese whey and their correlation to the outgoing biogas yeld. An input compound to anaerobic digestion plants as MBGC can also be the slaughterhouse wastes, carefully evaluated (Castellucci et al., 2013), in relation to the requirements of the European Regulations on animal by-products (ABPs) in order to fix a starting point for future tests on their co-digestion in a micro-scale pilot digester. The purpose was to define optimal feed ratio values which ensure an increasing content of methane in the outgoing biogas. With reference to small size and power plants, it has been considered (Hamed M. El-Mashad et al., 2004) a 10 m^3 completely stirred tank reactor for anaerobic treatment of liquid cow manure under thermophilic conditions (50°C), using a solar heating system mounted on the reactor roof and simulating the results obtained by two different system models. In consideration of the peculiar characteristics of MBGC, which make it particularly suitable for distributed and pervasive use, it has been examined a study (Plöchl et al., 2006) about the currently use of biogas in developing countries, that can certainly be improved by a more efficient way of producing and storing the biogas; as a consequence, it could become an opportunity to provide the neighborhood with biogas as an energy source for cooking and lighting and a possible electric energy production by the use of mini-scale generators. The possibility to obtain other products, in addition to biomethane, has been investigated (Oberti R. et al., 2013) through the design, manufacture and installation of an innovative two-stage pilot-scale plant, composed of hydrogenesis and methanogenesis reactors, for the production also of biohydrogen. With regard to the latter point, in the description of MBGC, a mention has been made of another patented device, called HWFC, whose function is to extract hydrogen from a fluid. This aspect will be presented in a forthcoming work as it is outside the scope of the present article which aims, instead, to describe the MBGC, a plant of small size, which can be made with components easily available on the market and installed in a distributed way, near the production sources of the waste biomass and close to the use of biogas and of its by-products such. In section 3, a case study will be presented in order to help the reader to better understand the method and device described in this article.

2. Materials and Methods

2.1 Description of the MBGC Plant

The MBGC method developed consists of the following subsequent stages:

- *hydrolysis, by hydration;*

- *acidogenesis;*

- *acetogenesis;*

- *methanogenesis;*

the last three phases are obtained by means of specific bacterial consortia[1]

- *simultaneous gravimetric separation of a lighter (mainly oleic) phase, and a heavier (mainly protein) phase;*

- *gravimetric separation of solutions of NPK salts of different concentrations;*

- *withdrawal of clarified water.*

The MBGC device is shown in the figures 1 and 2, whose letters and numbers are indicated in brackets in this text. (A) indicates the device, fitted to decompose and to separate the components of a biomass mixture. The basin (1), thermally insulated on the outside surface, is divided into the zones V1, V2 and V3, that are all communicating and separated by suitable baffles. The two zones V1 and V2 are in communication through a vertical opening between the end of the baffle (3) and the wall (1b); the baffles (4), (5), having a height equal to half of the baffles (2), (3), are transversely arranged to the baffle (2) and inside the third zone (V3), that is in communication with V2 by means of a perforated pipe (6), positioned at half the height of (2). The baffles (2) and (3) and the transfer pipe (6) define a path that must be traveled by the biomass mixture. The waste biomass to be treated run into the beginning of V1, through an inlet perforated pipe (7); at the bottom of V3 it is positioned an outlet pipe (8) for the withdrawal of clarified water from half the height of (2). In addition, along said path, they are positioned some submerged pumps (P1, P2, P3, P4, P5, P6), whose function will be specified later on. The zones V1 and V2 are heated to a temperature suitable to favor the biological processes of the mesophilic regime (typically comprised between 30 and 60 °C) and to sustain a slight excitation through convective motions. In the upper part of the basin (1) they are placed two blocks (B) and (C), each of which includes a plurality of vertical pipes. The upper block (B), of greater development in height, preferably made of plastic material (PE, PVC or similar) and the lower block (C), made of metal, are separated by a gap (9). The lower block (C) is cooled by means of a coil (not shown in figures 1, 2) crossed by a heat transfer fluid suitable to slightly lower the temperature of (C). The blocks (B) and (C) are inserted so as to obtain also a bottom gap (10) and an upper gap (11). At the ends of (10) and (11), they are positioned two pipes (12) and (13), on which they are made a plurality of holes (12a) and (13a) respectively, aligned along a generatrix of said pipes. To operate, the device (A) uses a hydro-dynamic state of communicating vessels, so as to reduce the waste of mechanical energy for the necessary advancement movements of the organic matrix. The flow of the waste biomass to be treated, indicated by the arrow (I), runs into V1 and is homogeneously spread through the holes (7a). The so obtained biomass mixture goes across the various areas in which the basin (1) is divided, and it is subject to various chemical-biological reactions: • in V1 it is implemented the hydrolysis, constituted by the splitting action of the water, by hydration, favored by conditions of high temperature; • in the final stretch of V1 it

is implemented the acidogenesis by specific bacterial consortia; • in the area comprised between V1 and V2, it is carried out the acetogenesis by specific bacterial consortia; • in V2 it is implemented the methanogenesis by specific bacterial consortia. In this zone, because of the larger section, the flow speed will be lower, in order to have a higher permanence time that favors the massive production of CH_4 and the gravimetric separation of a mainly oleic phase, lighter and a protein predominantly phase, heavier; • in the final stretch of V2 it is withdrawn a given quantity of the biomass mixture through the submerged pumps (P1) and (P2) and it is recycled to the beginning of V1; in particular (P1), placed in the upper part, recycles the mainly oleic mixture, while (P2), placed in the lower part, recycles the protein predominantly mixture; • in the transit from (V2) to (V3), through the pipe (6), placed at mid-height of the liquid phase, a horizontal flow is generated; • inside V3, following the generation of said horizontal flow, a widespread and different gravimetric action on the various components present in the biomass mixture occurs, obtaining their deposition in the different sectors provided by means of (4) and (5); the submerged pumps (P3), (P4) and (P5) withdraw the NPK salts of different concentrations from those sectors; • in the terminal portion of V3, the liquid mass is composed almost exclusively of water, that is withdrawn by the outlet pipe (8); • in the terminal portion of V3, at the top and in the proximity of the surface of the liquid phase, it is withdrawn the liquid, still containing oleic traces, that is recycled at the beginning of V1; this withdrawal is obtained through (P6) and in suitable amount to the processes of dilution to be implemented at the beginning of V1 , in order to correctly condition the waste biomass.

Note: [1]Not indicated below as they are outside the scope of this article

The gases generated during the degradation and digestion (CH_4 and CO_2) are collected in the gap (10) above the liquid mass and they are gravimetrically separate: the CO_2, heavier, tends to remain in the lower part, from which it will be extracted through the holes (12a), while the methane, lighter, will rise up to the upper gap (11), from which it will be extracted through the holes (13a). Inside the gases generated by the reaction it is also present the steam that, passing through the vertical channels of the lower block (C), condensate and returns in liquid form inside the fluid mass below; this condensation is obtained by lowering the temperature of the vertical channels of the lower block (C) and reaching the saturation condition (dew point). In the final stretch of V1 and in the zone between V1 and V2, in which are carried out the acidogenesis and the acetogenesis, a system of homogeneous and diffused lighting can find place (Farné, S., Lavanga, V., SDNA), in order to prevent the formation of H_2S due to a photosynthesis in absence of oxygen.

2.2 Biochemical-mathematical Model

The most abundant products resulting from the biological digestion of an organic matrix in the absence of oxygen are biomethane and carbon dioxide. The percentages of gas produced are variable and methane can reach 50-70% of the total gas phase. During methanogenesis, methane is obtained mainly from these two reactions:

$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$ & $CH_3COOH \rightarrow CH_4 + CO_2$

Considering the variability and complexity of the incoming waste biomass (organic waste, food waste, slurry, sewage, manure, wastewater etc.), further products from anaerobic digestion can be obtained: for example, the ammonia that comes from the demolition of proteins. In the case of anaerobic digestion of an organic matrix with

the $C_aH_bO_cN_d$ formula, the overall stoichiometric relationship can be represented by the formula (Cecchi et al., 2005):

$$CaH_bO_cN_d \rightarrow nC_wH_xO_yN_z + mCH_4 + sCO_2 + rH_2O + (d - n \cdot x) NH_3 \quad (1)$$
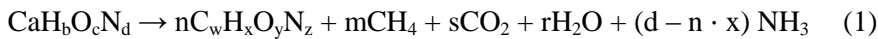
Where,

s = a − nw - m

r = c − ny − 2s

2.2.1 Speed and laminar motion

At the entrance of the basin there is the input waste biomass and, to be optimal, the digestion process must have a non-swirling trend. It must be ascertained that the speed of the semi-fluid biomass mixture, compatibly with the geometry of the basin, is not the cause of a turbulent motion. First of all, speed analysis is performed to make sure that the semi-fluid biomass mixture is characterized by a laminar motion. The average speed v can be calculated, in every zone of the basin, by the formula of Chezy (2), (Farné, 2015).

$$v = K_0\sqrt{RI} \qquad (2)$$

Where,

I= - (dH/dS)

H : pressure drop

S : length of the considered section

K_0 : roughness coefficient calculated by the Bazin's formula (3), (Farné, 2015)

$$K_0 = \frac{87}{1+\frac{c}{\sqrt{R}}} \qquad (3)$$

c: tabulated value depending on the nature of the internal walls

R = A/P : hydraulic radius

A = b*h : section area

P = b + 2h : wet perimeter

b : base of the zone

h : height reached by the biomass mixture

Having calculated v in V1 and V2, it is possible to calculate the Reynolds number (4), to verify that its motion is laminar, in order to assure the optimal conditions for the anaerobic digestion (Farné, 2015).

Re= (ρvd) /µ   (4)

Where, ρ : density of the biomass mixture, v : speed with which the biomass mixture moves, d : length of the characteristic of the surface along which the fluid moves, µ : viscosity.

2.2.2 Gravimetric separation

At various points of the device, in the recycling phase at the end of the second zone and for the entire duration of permanence in the third zone, the gravimetric separation of the fluid is used. It is operated, at the end of the second zone, to divide the oleic and the protein fractions, in order to recycle them, also by means of a specific device (Farné, S., Lavanga, V., GSMF). In the third zone, by means of two baffles, the gravimetric separation is used to divide the fluid into three different types of NPK salts. Due to the phenomenon of the phase separation, depending on the Reynolds number (4) of the flow, the final velocity (Mostafaiyan M. et al., 2015) in which the heavy phase settles down and the light phase rises up can be calculated employing the formulas (5), (6), (7)[2]:

Newton's law $\quad V_f = 1.74 \cdot \sqrt{\dfrac{gD_p(\rho_h - \rho_l)}{\rho_c}} \qquad$ for Re $\geq$ 500 $\qquad\qquad$ (5)

Stoke's law $\quad V_f = \dfrac{1000gD_p^2(\rho_h - \rho_l)}{18\mu_c} \qquad$ for Re $\leq$ 2 $\qquad\qquad$ (6)

Intermediate law $\quad V_f = \dfrac{3.54g^{0.71}D_p^{1.14}(\rho_h - \rho_l)^{0.71}}{\rho_c^{0.29} - \mu_c^{0.43}} \qquad$ for 2$\leq$ Re $\leq$ 500 (7)

Where,

V_f : final velocity

D_p : particle diameter

μ : viscosity

ρ : density

g : gravity constant

the subscripts h, l, and c denote the heavy, light and continuous phases, respectively.

2.2.3 Biomass characteristics

The following parameters are considered (Preto R., 2016):

- TS (total solids): it is the dry substance contained in the biomass, that can be digested by the bacterial consortia and converted in biogas and salts. The quantity is determined by drying a sample in an oven at 105 °C for 24 hours.

- TVS (total volatile solids) = y% of the total solids (TS): organic part, within the total solids, that can produce gases. It is the fraction of dry substance which is volatilized by evaporation at 550 °C up to constant weight. (8)

- NPK = (100-y)% of the total solids (TS): concentration of salts contained in the total solids (9)

- WET = x% of the TS inside the biomass; the remaining (100- x) % is the water content (10)

- COD: chemical oxygen demand: quantity of oxygen consumed for the oxidation of the organic substance.

[2]the numerical coefficients depend on the units of measurement chosen, an aspect not important for the purposes of this article

This quantity is determined through the use of a strong oxidizing chemical agent i.e. potassium dichromate ($K_2Cr_2O_7$) in an acid medium.

- BOD5: amount of oxygen consumed in 5 days. The quantity is determined under controlled conditions due to the biological oxidation of the organic substance present in the sample.

- BOD_L: 20-day biological oxygen demand.

- TOC (Total Organic Carbon): total organic carbon. The TOC of a wastewater can be used as an indication of its polluting load and in some cases it may be possible to establish a correlation between the values of TOC, BOD and COD.

2.2.4 Reactor Management Parameters

They determine the process according to the residence times of the biomass to be degraded in the reactor, the concentration of microorganisms, the yields of biogas production in relation to the volume of the reactor and the characteristics of the treated substrate. These parameters are divided into (Preto R., 2016):

- Available volume for digestion: V that is equal to (V1 + V2) in the case of MBGC

- Average hydraulic residence time (HRT - HYDRAULIC RETENTION TIME): ratio between the volume of the considered reactor and the volume added every day. HRT is a conventional parameter in stationary digestion reactors; in MBGC a volume enters and an equal volume is withdrawn, by overflowing, having to keep the operating volume constant.

- Average sludge residence time (SRT – SLUDGE RETENTION TIME): ratio between the total mass of volatile solids (mass that passes into the gaseous state over a certain temperature) present in the reactor and the flow of solids extracted from the reactor itself.

- Organic volumetric load (OLR) of substrate applied to the reactor: quantity of substrate entering the reactor referred to the volume unit of the reactor itself and to the time.

- Organic load related to biomass or volatile solids in the reactor (CF): defined as the quantity of volatile substance present in the reactor per unit of time.

- Estimated volumetric organic load: it is the amount of organic matter loaded daily per useful digestion unit per day.

- Specific gas production (SGP - SPECIFIC GAS PRODUCTION): produced between the volume of gas generated and volatile solids. The specific gas production (m^3 biogas / kg fed substrate) is the quantity of gas that is produced per quantity of volatile substance fed to the reactor. This parameter, widely used to define the yields of the anaerobic digestion processes, is actually closely linked to the biodegradability of the treated substrate rather than to the properties of the process adopted.

- Biogas production speed (GPR): flow rate of biogas produced compared to the reactor volume and time. The biogas production rate (m^3 biogas / day) / (m^3 reactor) is defined as the flow rate of biogas produced in

relation to the volume of the reactor and the time.

2.2.5 Flow Rates

A waste biomass with variable composition and humidity enters the MBGC basin. The numbers and percentages indicated below are realistic but may vary based on the actual composition of the incoming waste biomass; they are mainly reported to illustrate the functioning of MBGC and its productivity. For the sake of simplicity, we assume that the density of the waste biomass is equal to that of water, i.e. 1 kg/dm^3. The compound of the biomass mixture should be 90% water and 10% total solids (WET = 10%) but obviously it is not certain that this is the case. The total solids (dry matter) of the waste biomass can fluctuate between 10% and 50%. To estimate its humidity rate, it is foreseen to execute a composition analysis at regular intervals, in order to calculate a mean value of the associated humidity. If this is not within the parameters, it will be necessary to withdraw water from the end of the cycle to recalibrate it:

$$Q_i = Q_0 + Q_h \qquad (11)$$

Where,

Q_i is the flow rate of the biomass mixture that starts the cycle

Q_0 is the flow rate of the waste biomass supplied at the initial part of the system; it is composed by TS and by its intrinsic humidity, but it is not mixed with external water;

Q_h is the flow rate of water provided to increase the humidity of the waste biomass

Q_0 is composed by a fraction of protein TS and of oleic TS, depending on the type and composition of the waste biomass. Assume that TS are globally the 20% of Q_0 subdivided in:

protein TS = $0,15 \cdot Q_0$ $\qquad$ (12)

oleic TS = $0,05 \cdot Q_0$ $\qquad$ (13)

At the end of V2, after 10 days of stay in the MBGC, the BMP (fig. 3) diagram (test that assesses the methanogenesis potential of an organic matrix), gives the percentage of the digested biomass. With reference to formulas (8) and (9), assume that:

-   the digested percentage is the 80% of TS

-   TVS = TS $\cdot$ y% = ST $\cdot$ 0,8

-   NPK = TS $\cdot$ (100-y)% = TS $\cdot$ 0,2

from this, it follows that:

-   Biogas produced = 80 % of TVS = $0,8 \cdot (0,8 \cdot TS)$ $\qquad$ (14)

-   Salts produced = 80 % of NPK = $0,8 \cdot (ST \cdot 0,2)$ $\qquad$ (15)

-   Not digested = 20 % of TS $\rightarrow$ from formulas (12) and (13):

o Protein fraction not digested:

$$Q_P = 0{,}2 \cdot (\text{protein TS}) = 0{,}2 \cdot 0{,}15 \cdot Q_0 = 0{,}03 \cdot Q_0 \qquad (16)$$

o Oleic fraction not digested:

$$Q_O = 0{,}2 \cdot (\text{oleic TS}) = 0{,}2 \cdot 0{,}05 \cdot Q_0 = 0{,}01 \cdot Q_0 \qquad (17)$$

At the end of V2, the biomass mixture has three fairly distinct phases:

- the protein fraction not digested on the bottom side;

- the oleic fraction not digested in the upper part;

- salts and water, in the middle.

The most part of the protein and oleic fractions will be recycled to the beginning, while salts and water will continue the cycle through a pipe perforated along its surface and placed at about half the height of the baffle. The pipe (fig. 4), closed at the ends, is extended between the second baffle and the wall of the third zone and therefore it has a length equal to:

L = b2+b3;

where

b2 = base of the second zone

b3 = base of the third zone

Furthermore, to ensure a correct and continuous flow of the fluid, without preferential routes, it was thought to establish a relationship between the holes distributed on it and its internal diameter.

$$(\text{internal diameter area}) \leq \sum (\text{hole areas})$$

The flow that continues the path in V3 will be split into its components during the processes of the third zone thus obtaining water and three different types of salts. The salts will be divided according to their density into 3 sectors created specifically to contain them:

$$Q_3 = (NPK1 + NPK2 + NPK3 + Q_4)$$

Where, Q_3 = flow in the third zone, Q_4 = water flow.

It is particularly important to highlight that, thanks to the setting "continuous" of MBGC, the digestion products will be expelled due to the hydraulic thrust so it will not be necessary to stop the plant. The operator, helped by special tools, will choose the quantity of salts to be withdrawn and the periodicity of this withdrawal.

3. Results and Discussion

3.1 Case study: description of a complete biomass treatment cycle

The following dimensions of the MBGC have been taken into consideration: 2,5 m x 10 m x 2,5 m. It has been calculated that this basin is able to treat a volume around 1,000 dm^3 of waste biomass per day, corresponding to a

mass of 1,000 kg due to the previous hypothesis. It is assumed that it contains a 20% of total solids. The percentage will be appropriately adjusted through a system of communicating vessels that will bring other 1,000 dm^3 of recirculated fluid back to the start of the process, in order to bring WET to the desired value of 10. In this way, the incoming waste biomass becomes a total volume of 2,000 dm^3 of biomass mixture, in which the percentage of TS is 10%. It has been highlighted that an innovation of MBGC is the characteristic of being "continuous": under steady state conditions, the organic matrix continues to move, driven by what is loaded daily in V1 and pushing out daily the by-products in V2 and in V3. To describe the flow and the production potential of the organic matrix, let's focus on a waste biomass entering from the outside of 1,000 dm^3 (and becoming a biomass mixture of 2,000 dm^3), assume that it is the only "active" quantity and follow its movement inside the MBGC path. This description and the results obtainable in a complete thirty days treatment are summarized in Tab. 1 and in figures 5-11. It is evident that this is a schematization and that the results could vary in reality but, it is considered useful for a better understanding.

The waste biomass of 1,000 dm^3 is withdrawn from the previous storage (eg. Imhoff tank) of first transfer from the waste systems (eg. a stable) and is composed by a part of 700 dm^3 of protein fraction taken from the lower part and a part of 300 dm^3 of oleic fraction taken from the upper part of the Imhoff tank. The withdrawal takes place by two pumps located respectively at the bottom and at the top of the same Imhoff tank and sent through a pipeline to the entrance of the MBGC basin. Using formulas (12) and (13) it is obtained:

protein TS = 0,15 * Q_0 = 150 Kg

oleic TS = 0,05 * Q_0 = 50 kg

Considering the zone V1, whose extension in length varies from 0 to 10 m (ideally divided into sectors of about 3m):

- the entry point of the 1,000 dm^3 of waste biomass is positioned at the beginning of the biomass mixture inserted the day before;

- the introduction point of the recirculated water (100 + 100 dm^3 from V2 and 800 dm^3 from V3) is positioned at about 1 m, to facilitate a preliminary mixing;

- a mixer, consisting essentially of two perforated pipes and a pump, is positioned so that one pipe is at about 0.2 m and the second one at about 2.8 m from the insertion point of V1. The perforated pipes are about 1.5 m high, with holes facing each other, and one has the task of aspirating the biomass while the other has the task of returning it to V1 (i.e. in its first sector), making it homogeneous, also by means of a specific device (Farné, S., Lavanga, V., MHLM).

At the same time as mixing, the heating process takes place, that has the function of accelerating the hydrolytic phase. At about 0.3 m from the beginning of V1, a vertical finned coil is placed in which a heat carrier fluid flows at about 55 °C, previously heated by the passage in the condenser of a heat pump. The heat transfer fluid, exiting the coil, passes into the radiant floor circuit of zones V1 and V2, conditioning it at an average temperature of 40 °C, optimal for mesophilic digestion. Underfloor heating will trigger convective motions and horizontal translation in the biomass mixture, helping to homogenize it in its path from the first to the tenth day.

By the BMP test (fig. 3) it is known when the peak of hydrogen production occurs. Suppose it is on the fourth day and therefore in correspondence with the transfer from V1 to V2. It is possible to extract this hydrogen dissolved in the liquid phase with a deviation (not shown in materials and method): the biomass mixture, exiting V1 can be conveyed into a patented device called HWFC which allows the extraction of hydrogen, and is then reintroduced in the flow of V2. This arrangement would also improve the subsequent methanogenesis process. The quantity of methane and carbon dioxide globally produced is given by formula (14):

produced biogas = 0,64 * ST = 0,64 * 200 kg = 128 kg

of which approximately (Cecchi et al., 2005):

biomethane = 2/3 of produced biogas = 85.3 kg

carbon dioxide = 1/3 of produced biogas = 42.7 kg

These biogas quantities are separated and collected by the means described in the "materials and methods" chapter. According to the BMP chart (fig. 3), assume that about the 80% of the biomass mixture will be digested in 10 days; to recover the undigested 20%, a recirculation system is activated at the end of the zone V2 which sends the undigested back to the beginning of the process, so as to oblige it to continue with the anaerobic digestion. The undigested mass will be about 40 kg as obtained according to formulas (16) and (17):

Protein fraction not digested: $Q_P = 0,03*Q_0 = 30$ kg

Oleic fraction not digested: $Q_o = 0,01 * Q_0 = 10$ kg

Assuming that only the 95% of the undigested biomass is effectively taken, a quantity of 28.5 kg diluted in a fluid volume of 100 dm^3, and another of 9.5 kg, diluted in a fluid volume of 100 dm^3, are withdrawn from the top and from the bottom respectively and is sent back at the beginning of the process.

In V3, the digested material will settle into three sectors according to its density: the thicker fraction will fall at the beginning while the less dense will continue in the other two sectors. Using formula (15) it is obtained:

Salts produced = 0,8 * (ST * 0,2) = 0,16 * 200 kg = 32 kg

At day 30, the waste biomass, that have started its treatment 30 days before, ends its path; a volume of 800 dm^3 (containing 5% of undigested oleic, equal to 0.5 kg) is withdrawn from the top of the basin and sent back to the entry point of V1, while a volume of 1,000 dm^3 of clarified water is withdrawn from the basin. In this way, the treatment is complete.

A note about NPK salts extraction: in the in the above described configuration and in steady state conditions, NPK salts will be extracted weekly from the three sectors inside V3. This periodicity allows a significant accumulation of NPK salts. The extraction process will be performed before the daily input of waste biomass (1,000 dm^3) so as to create a lower overall volume. In fact, a fluid volume of 600 dm^3 will be withdrawn which, distributed over a total area of 25m^2, causes the liquid level to drop by about 0.024 m. When entering the 1,000 dm^3 of waste biomass, the clarified water spill (from the half-height pipe) will be only 400 dm^3 and not 1,000 dm^3 as in normal conditions. A total of 224 kg will be accumulated in 7 days. This quantity, divided by the 3 sectors, corresponds to an average of

about 75 kg in each that, diluted in 200 dm^3 of fluid, correspond to an average concentration of approximately 37.5%.

3.2 Advantages of MBGC

As previously illustrated, MBGC has peculiar characteristics that give it several advantages:

- Potentiality: MBGC can produce limited powers (from 1 to 10 kW), so there are no similar systems.

- Compactness: in the configuration presented in this article, a volume of 62.5 m^3 and dimensions (2.5x10x2.5) m are enough to absorb a daily waste biomass of 1,000 kg (with 20% of generic TS) to start the process and to obtain a power of 10 kW. Furthermore, MBGC can be completely buried, also to avoid visual impacts.

- Cost-effectiveness of materials: MBGC is made of standard, cheap and easily available construction materials.

- Versatility: MBGC has been designed to adapt to multiple operational contexts like small farms, condominiums, buildings not connected to the sewage network, residential agglomerations in rural areas, small businesses and industries, villages etc. In addition, it takes a few days to install.

- Energy savings: MBGC is entirely thermally insulated, so that once the process is triggered, its energy consumption is extremely low and can also be supplied from renewable energy sources.

- Savings in utility bills: the production of biomethane by the MBGC gives the end user the opportunity to use it to generate electric energy and heat.

- Savings on waste disposal costs: the MBGC allows to save on the costs that a structure must incur to dispose of waste as they are used to feed the same.

- Economic return from by-products and from the injection of excess power into the grid: NPK salts, carbon dioxide, methane and electric energy can be sold to make an additional profit.

- State incentives: the MBGC can take advantage of state incentives as it produces energy from biomass which turns into savings on the purchase of the same (Capodaglio et al. 2016).

4. Conclusions

The physical structure of the device was described along with the principles and methods, simultaneously with its operation. Later, a model of calculation of the system was introduced, one of the main subjects of this paper. The analysis model made it possible to relate the geometrical and biochemical parameters to the operating conditions of the plant, allowing a formulation to be obtained for calculating the producibility of the plant. Based on the calculation model and on some assumptions, it was possible to make a simulation of its operation. A description of the biomass flow inside the various zones of the MBGC has been illustrated, following a complete cycle of 30 days. The results have highlighted the behavior of a standard module, characterized by a good level of producibility in terms of biogases (methane and carbon dioxide), NPK salts and clarified water, which could be appropriately

replicated to obtain the level of productivity sought by a possible customer. As a consequence, the benefits of MBGC have been listed. The MBGC development and application studies are still ongoing and they will be the subjects of future works.

PATENTS: MBGC - Method for anaerobic digestion and device for implementing said method - Publication Number WO/2016/092582, Publication Date 16.06.2016, International Application No. PCT/IT2015/000306, https://patentscope.wipo.int/search/en/detail.jsf?docId=WO2016092582

Declarations

Competing Interests Statement

The authors declare no competing financial, professional and personal interests.

Consent for publication

We declare that we consented for the publication of this research work.

Code availability

The programming code that we have used for this research is available and authors are willing to share when it is required.

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TABLES

Table 1 - Complete treatment in 30 days of a biomass mixture

Days	1-2	3-4	5→9	10	11→30
Zone	V1	V1-V2	V2	V2-V3	V3
Process	Introduction of the waste biomass, mixing with recirculated fluid, homogenization and heating	The biomass mixture arrives, in day 3, in the final part of V1 and enters, in day 4, in the initial part of V2, in which it is partially transformed into acetic acid	The previously formed acetic acid is transformed into methane and carbon dioxide	The biomass mixture arrives at the end of the zone V2. Undigested biomass sent back to V1	The biomass mixture enters and proceeds in V3. Salts separation due to density
Waste biomass dm^3	1,000				
Recirculated fluid from V2 dm^3	200			200	
Recirculated fluid from V3 dm^3	800				800
Total biomass mixture dm^3	2,000	2,000	2,000	1,800	1,800
Phases	Hydrolysis	Hydrolysis + acidogenesis (in V1); Acidogenesis + acetogenesis (in V2)	Methanogenesis	Methanogenesis	
Reaction		Acidogenesis: $C_6H_{12}O_6 \rightarrow$ CH_3CH_2COOH+ $CH_3COOH+CO_2+H_2$	$4H_2+CO_2 \rightarrow CH_4+2H_2O$ $CH_3COOH \rightarrow CH_4+CO_2$	$4H_2+CO_2 \rightarrow CH_4+2H_2O$ $CH_3COOH \rightarrow CH_4+CO_2$	

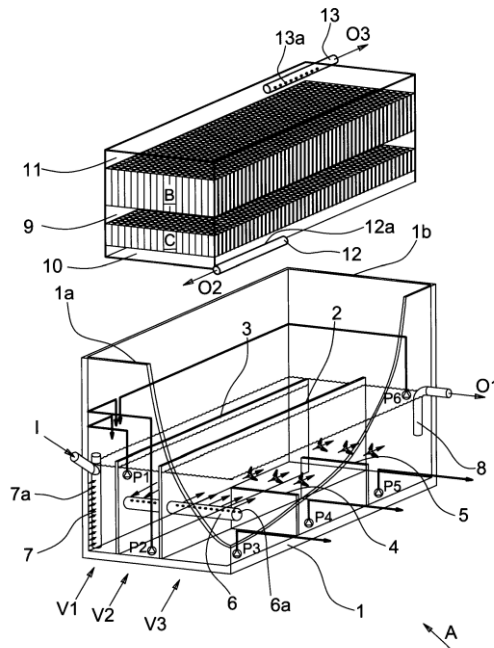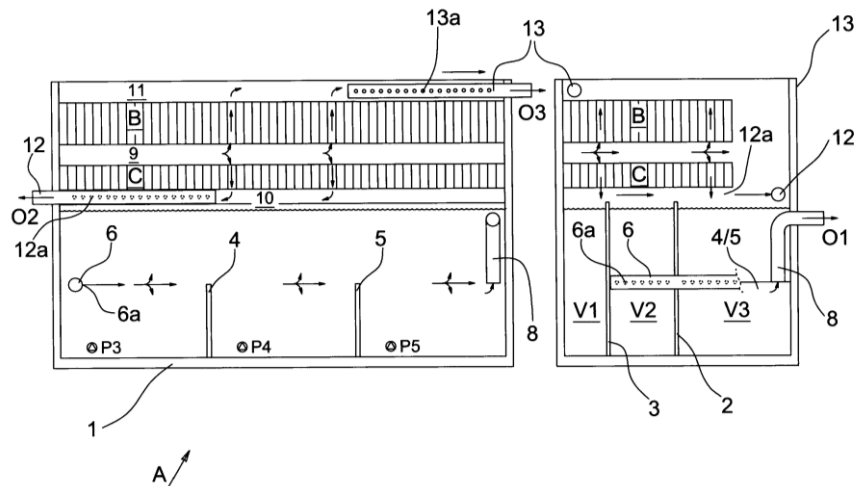|		Acetogenesis: $CH_3CH_2COOH+H_2O\rightarrow$ $CH_3COOH+CO_2+3H_2$			
By-products obtained			85.3 kg of CH_4 42.7 kg of CO_2		1,000 dm^3 of clarified water; 32 kg of NPK salts
Figures	5, 6	7, 8	9		10a, 10b 11

FIGURES

Fig.1 – Perspective view of MBGC

Fig. 2 – Orthogonal views of MBGC
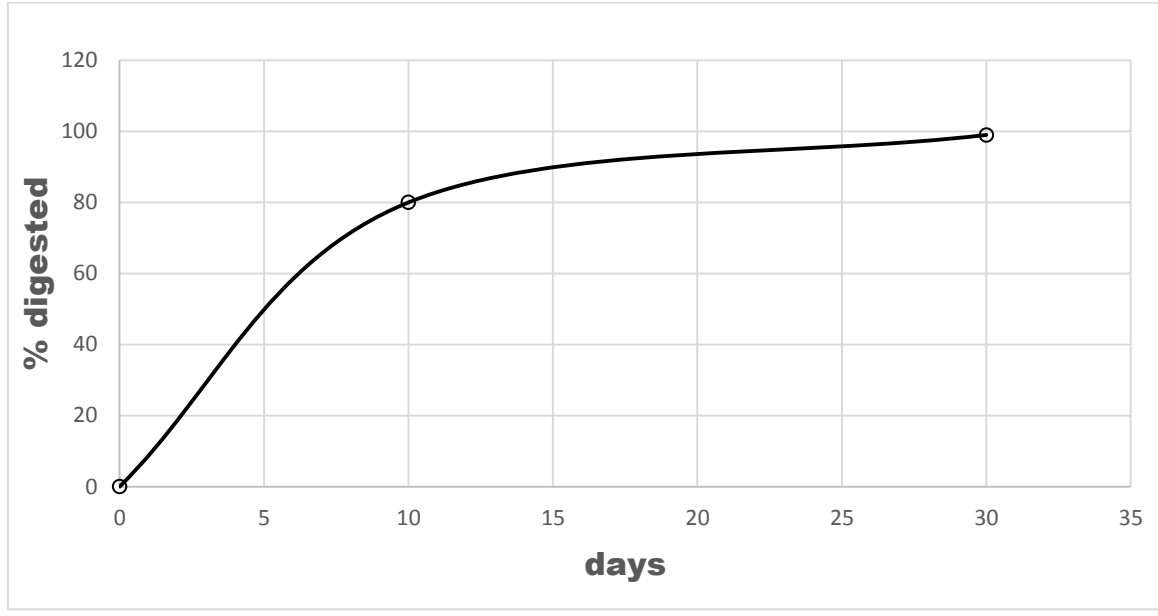
Fig. 3 - Example of a BMP diagram
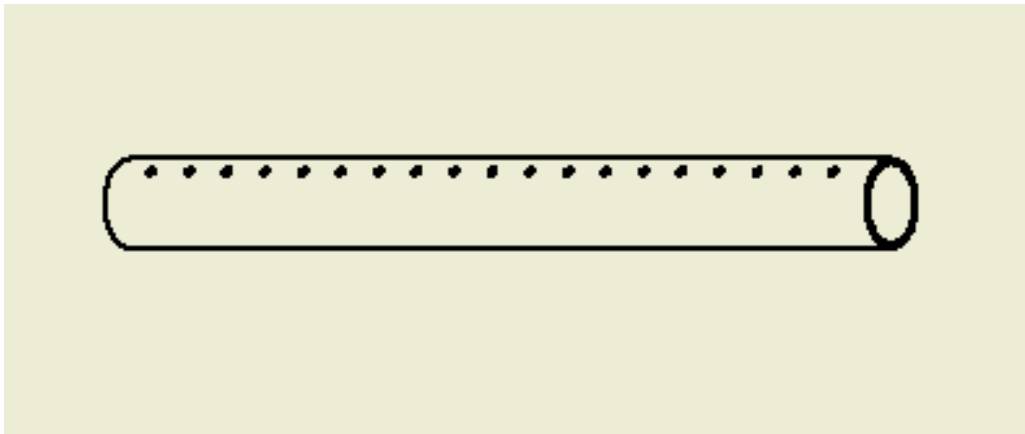
Fig. 4 - Connecting tube between V2 and V3 zones

Caption:

🟥 Waste biomass

🟨 Biomass mixture

🟧 Zone V1

🟦 Zone V2

🟩 Zone V3

🟦 Water (mainly)

🟫 Substrate already present in the basin

▬ Haloplines (daily position of the biomass mixture)
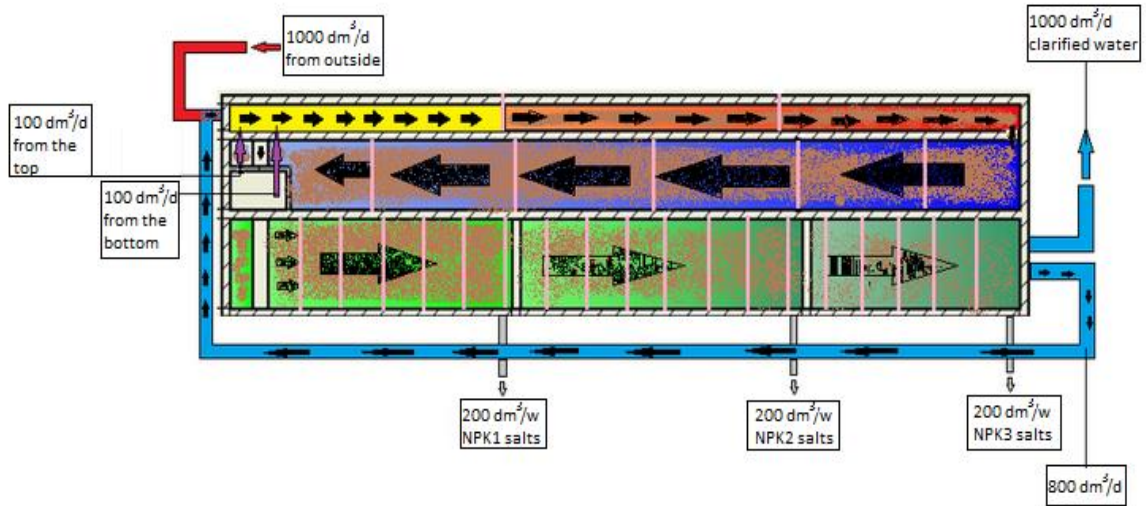
Fig. 5 - Day 1 in V1
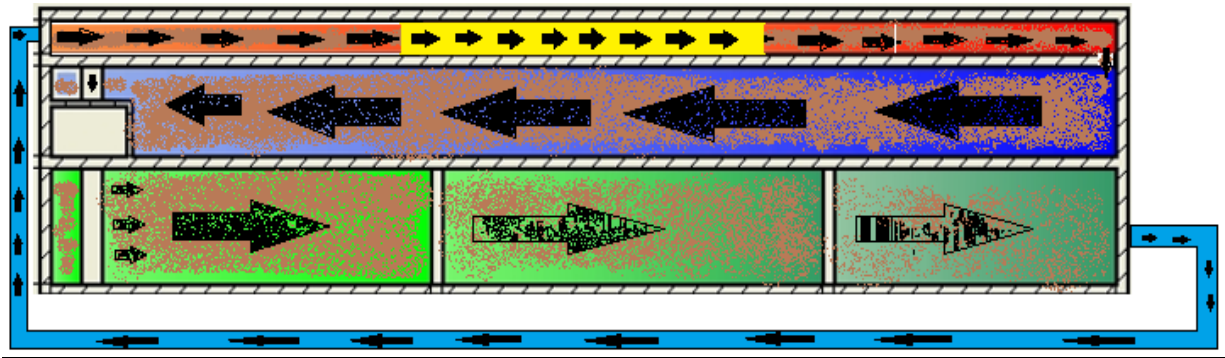
Fig. 6 - Day 2 in V1
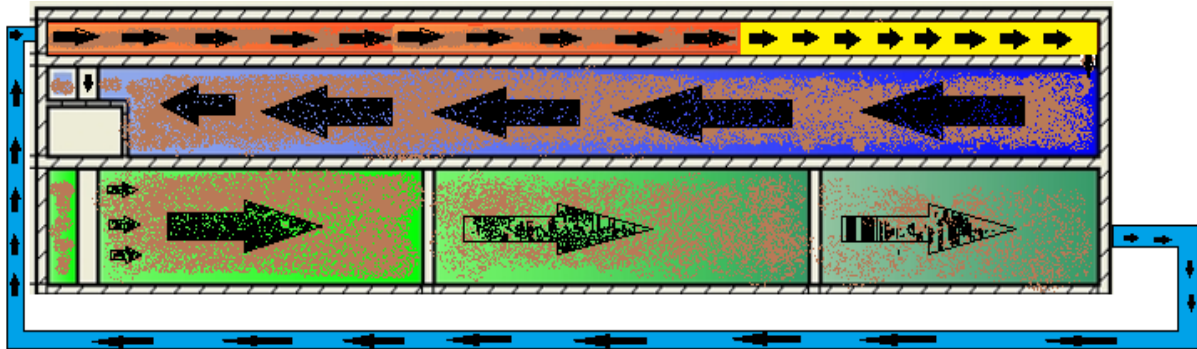
Fig. 7 - Day 3 in V1
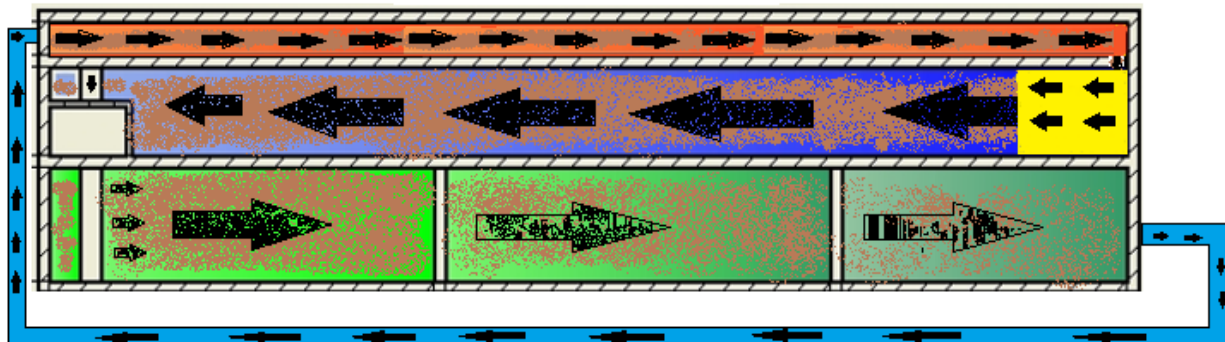
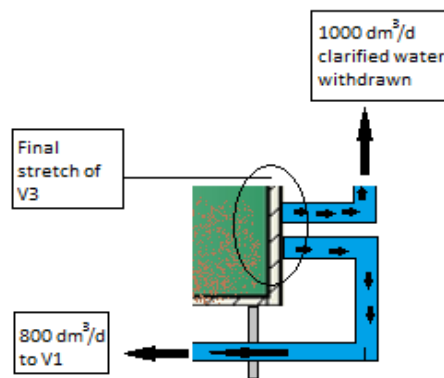**Fig. 8 -** Day 4 in V2
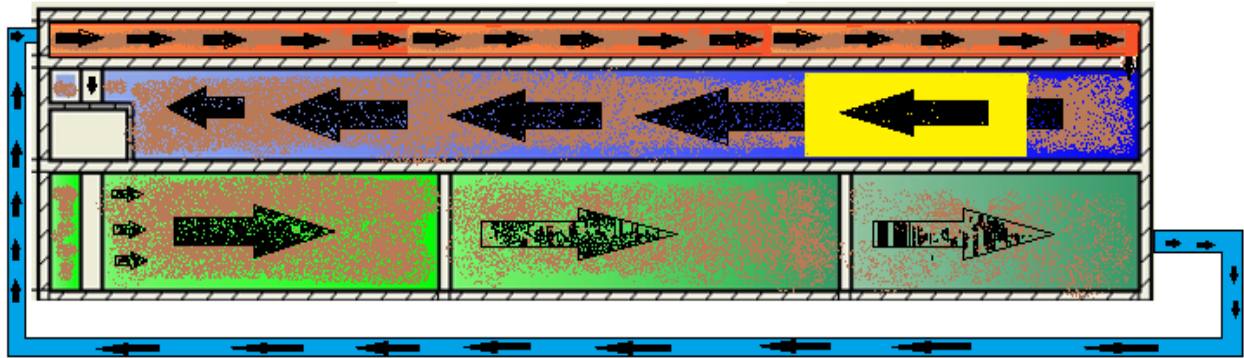
Fig. 9 - Days 5-6-7-8-9 in V2

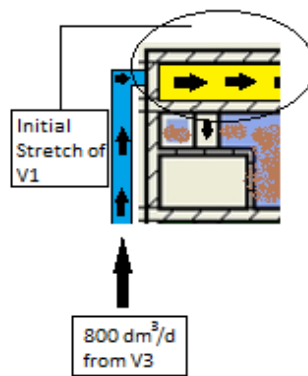**Fig. 10a** – withdrawn of recirculated water

Fig. 10b - Return of the recirculating water

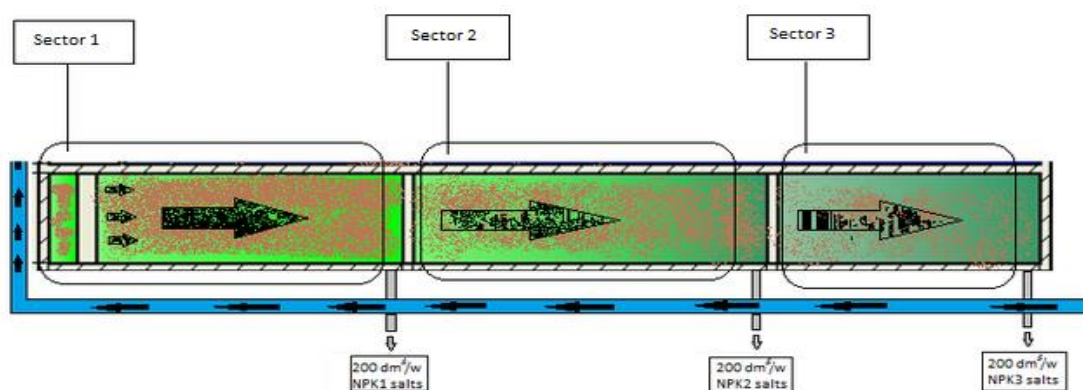**Fig. 11 -**Salt extraction