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(54) **Title:** ADVANCED CHEMICAL RECYCLING OF MIXED AND PURE WASTE PLASTICS WITHIN A MOLTEN METAL REACTOR

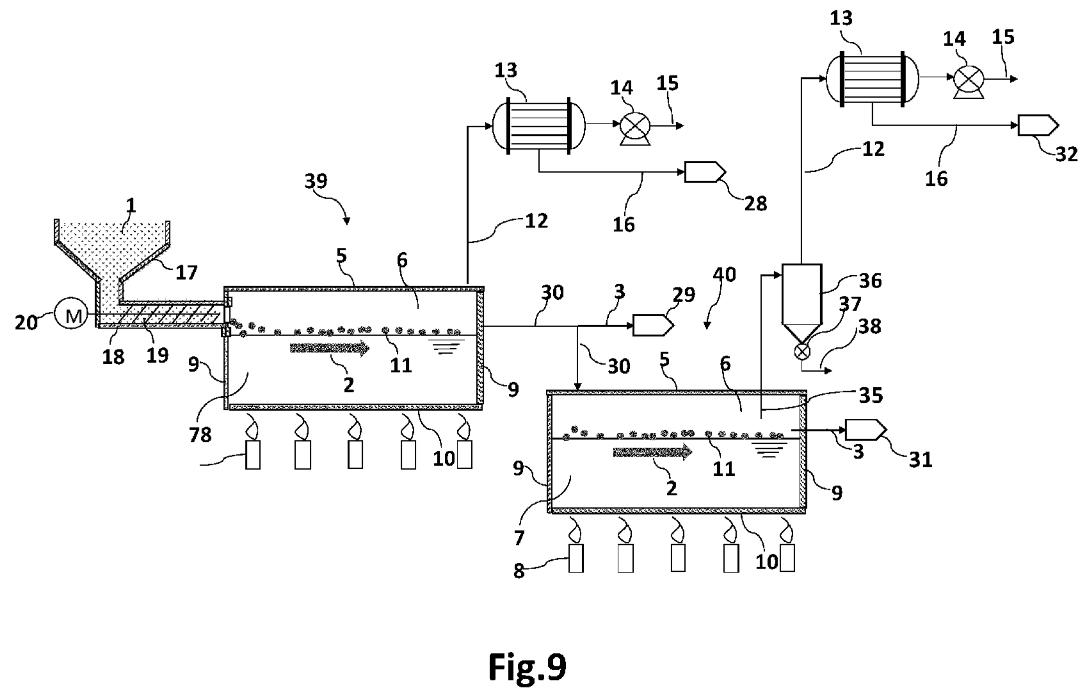

Fig.9

(57) **Abstract:** In a preferred embodiment there is provided a reactor system and method for recycling feedstock such as single or mixed plastics, for example polyolefins, comprising a charging device for continuous or discontinuous charging of the feedstock, the system characterised by a plurality of pyrolysis chambers arranged in series, wherein each pyrolysis chamber comprises a pyrolysis liquid selected from one or more pyrolysis liquids; one or more vapour removal lines; one or more liquid product drains; and one or more vapour and solid product extractors, wherein a liquid wax phase generated in a pyrolysis chamber is the feedstock stream for the subsequent chamber. Disclosed is a continuous process for the chemical recycling of mixed and pure plastics, which are pyrolysed on molten metal at an operating temperature of 160 to 700°C. The pyrolysis gases are condensed to pyrolysis oil and waxes. Long chain waxes may be recovered directly from the pyrolysis chamber as a liquid product.

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Title

Advanced chemical recycling of mixed and pure waste plastics within a molten metal reactor.

Field

The disclosure relates to the chemical recycling of mixed and pure plastics by pyrolysis.

Background

Plastics are derived from crude oil; they are generally not biodegradable but can be converted back into synthetic oil by pyrolysis. Pyrolysis is a thermal decomposition process that breaks plastic macromolecules into smaller ones, operating between 160 to 700°C without oxygen and, typically, at ambient pressures.

Plastics are difficult to recycle. As a result, most plastic waste is incinerated or landfilled. In 2018, by weight, up to 80% of the global waste plastic was landfilled or accumulated in the environment, and only 9% was recycled.

This invention applies pyrolysis to treat waste plastics. More information and discussions on the feed material treated in this invention, its pyrolysis and pyrolysis oil upgrading processes may be found in the following: (1) S. D. A. Sharuddin et al., A review on pyrolysis of plastic wastes, Energy Conversion and Management 115, (2016), 308–326; (2) B. Kunwar et al., Plastics to fuel: a review, Renewable and Sustainable Energy Reviews, 54, (2016), 421–428; (3) S. Honus et al., Pyrolysis gases produced from individual and mixed PE, PP, PS, PVC, and PET - Part I: Production and physical properties, Fuel, 221, (2018), 346–360; (4) Kim Ragaert, Laurens Delva, and Kevin Van Geem, Mechanical and chemical recycling of solid plastic waste, Waste Management, vol. 69, 24–58, (2017).

The European patent EP 2 233 547 B1 entitled "Method and chemical reactor for producing gaseous hydrocarbons derived from plastics materials" discloses a waste plastic pyrolysis process comprising an extruder and a screw reactor.

The extruder melts the plastic through mechanical friction and external heating. Then, the molten plastic is added to the screw reactor for pyrolysis. Inert substances such as ball bearings and catalysts may also be added. The ball bearings or other inert substances improve heat transfer, and the catalysts generally improve the reaction conditions. However, a catalyst is expensive and is, therefore, undesirable.

The US patent US 2017/0283707 A1 entitled "Process and apparatus for producing hydrocarbon fuel from waste plastic" discloses a pyrolysis system comprising a melt screw reactor, which pre-melts the waste plastic that is added molten into an auger-assisted rotary kiln pyrolysis reactor. Moreover, the pre-melting of the plastic assists in chlorine removal. The heat transfer within the rotary kiln reactor is assisted by ball bearings suspended in the plastic melt. These ball bearings are recirculated from the back of the rotary kiln to the front and are thought to improve the heat transfer within the rotary kiln. Three condensers condense the pyrolysis gases to generate different hydrocarbon streams. However, while adding ball bearings enhances the heat transfer to the waste plastic, the ball bearings must be removed from the pyrolysis solids and recirculated, which may be difficult and, hence, costly.

The PCT patent application WO 2018/000050 A1 entitled "Plant and process for pyrolysis of mixed plastic waste" discloses a batch process that adds molten plastic from a feeding screw to a stirred vertical batch pyrolysis reactor. The molten plastic remaining in the feeding screw provides a process seal. The char is transferred in batch mode to a fluidised bed burner, the heat output of which may provide the heat for the entire process. Disadvantages of this complex process include that it is a batch process and that the molten plastic remaining in the feeding screw may decompose, resulting in overpressures and corrosion of the screw.

The US patent 6,172,271 B1 entitled "Method and apparatus for reclaiming oil from waste plastic" discloses a pyrolysis system in which the plastic is mixed with heated sand before pyrolysis to improve the heat transfer to the plastic. In the first step, the plastic mix is dechlorinated at a temperature of 250-350°C. After dechlorination, the mixture is further heated with hot sand or a different additive agent to a pyrolysis temperature of 350-500°C. However, three disadvantages of using sand are (1) the heat capacity of sand is relatively low, (2) the sand may be abrasive, resulting the mechanical problems with the feeding screw, and (3) the sand must be removed and recycled to the inlet of the reactor resulting in additional capital expenditures.

The PCT patent application WO 2014/032843 A1 entitled "Process and system for whole tyres and plastic composites pyrolysis to fuel conversion and compound recovery" discloses a system for the recycling of whole tyres, coarsely cut tyres, large plastic pieces, plastic composites such as hoses or combinations of above into gases, liquids, and solids by direct heating in a pyrolysis liquid such as molten salt or molten metal.

The US patent US 2020/0299590 A1 entitled "Process and system for recovering hydrocarbons from oil sands and oil shale" discloses a pyrolysis system for producing synthetic crude oil from unconventional oil sources such as oil sands or oil shale.

The PCT patent application WO 2014/167139 A2 entitled "Process for the recycling of waste batteries and waste printed circuit boards in molten salts or molten metals" discloses a system for the recycling of printed circuit boards (PCBs) and similar materials by pyrolysis; specifically, by direct heat contact of the PCBs in molten salt. The separation of the light and heavy materials occurs within the separation chamber. This process avoids the inefficient process of sorting the batteries to type, size, or both and avoids shredding and pulverisation associated with many other processes.

The US patent 6,143,940, entitled "Method for making a heavy wax composition", discloses a process for making a heavy wax composition by operating a sub-atmospheric pyrolysis reactor. The US patent 11,091,700 B2 entitled "Process for the preparation of a C_{20} to C_{60} wax from the selective thermal decomposition of plastic polyolefin polymer" discloses another pyrolysis process for making a wax from plastics by operating a sub-atmospheric pyrolysis reactor. However, such sub-atmospheric or vacuum processes are expensive and difficult to operate.

The UK patent application GB 2388842 A discloses a continuous process of converting plastics (polyolefins) into lube oils or waxes. The plastic is added to the pyrolysis reactor molten, and at least some of the vapours are treated in a catalytic isomerisation dewaxing unit. However, melting the plastic before pyrolysis is expensive and unnecessary if a molten metal reactor is used.

The UK patent application GB 2473528 A entitled "Improvements in the production of wax products by the pyrolysis of plastics" discloses a plastic (polyolefins) to wax process using microwaves. However, microwave reactors have disadvantages over other reactors; for example, microwave treatment may be expensive as it is relatively high-tech compared to low-cost waste material.

The PCT application WO 2021/133884 A1 entitled "Circular economy for plastics waste to polyethylene via refinery FCC and alkylation units" discloses a plastic pyrolysis process separating the pyrolysis vapours into offgas, pyrolysis oil and, optionally, wax comprising a naphtha/diesel and heavy fraction, and char. The pyrolysis oil and wax are passed to a refinery FCC unit from which a liquid petroleum gas C_3-C_5 olefin/paraffin mixture fraction is recovered. The propane and butane fractions are then passed to a steam cracker for ethylene production. Such a process would, however, only be economical if the plastic pyrolysis process is integrated into an existing refinery process. This integration may only sometimes be possible or desirable, and is a complex task. A similar approach to WO 2021/133884 A1 is disclosed by US 10,233,395 B2 entitled "Process for converting mixed waste plastic (MWP) into valuable petrochemicals".

The PCT application WO 2022/207891 A1 entitled "Process and system for the recycling of composite plastic material, mixed and pure waste plastics" discloses a plastic pyrolysis process for mixed and pure plastics. However, the disclosed process is not suitable to treat materials such as mixed or pure plastics.

The present invention solves the problems described above. As a result, it provides a novel method for recycling waste plastics and obtaining pyrolysis wax, pyrolysis oil, and pyrolysis gases.

Summary

The invention, as set out in the appended claims, proposes a system and method to pyrolyse mixed and pure plastics by direct heat transfer to said plastics while in an accumulated wax phase or on top of molten metal, resulting in a quick process as the theoretically fastest heat transfer can be achieved. Equally as important as quick heat transfer is the avoidance of temperature spikes or, more generally, temperature gradients, which prevent long-chain molecules from accumulating, as they crack in locations in which there is a large temperature gradient. Target materials are pyrolysis oil or wax gained from plastic pyrolysis and pyrolysis gases, which may be burned for heat, re-powering the process, the generation of electricity, or a combination of these and other uses.

Experiments on a pilot-scale plant showed that plastic pyrolyses on molten metal at essentially the same yields and produces the same quality of products as that obtained from laboratory experiments using grams of plastic, for instance, published by S. Honus et al., Pyrolysis gases produced from individual and mixed PE, PP, PS, PVC, and PET - Part I: Production and physical properties, Fuel, 221, (2018), 346–360. This is due to three reasons: (1) rapid heat transfer from the molten metal to the plastic, (2) a minimum temperature gradient, if any, along the surface of the molten metal and (3) the ease of scale-up of a surface-bound reaction, for which doubling the surface area doubles the throughput.

Surprisingly, the experiments also revealed that after adding more significant amounts of polyolefin plastics to the reactor, for example ca. 1 kg, long-chain waxes such as $C_{60}H_{122}$ or longer accumulate and form a liquid layer on the molten metal. These long-chain waxes have boiling points well in excess of 460°C. Once a liquid wax phase forms, very little or no pyrolysis oil is collected (ref.: Frank Riedewald et al., Chemical Recycling of Polyolefins with the Molten Metal Reactor at 460°C, Chemie Ingenieur Technik, (2023), 95(8), 1, 332-1,338). These waxes can be recovered by draining them from the reactor intermittently or continuously. Moreover, these waxes, liquid at the operating temperature of 460°C, continue to provide direct heat transfer conditions to the newly added plastics.

According to the first aspect of the present invention, there is provided a pyrolysis system for recycling a feedstock composed of mixed plastics or single waste plastic streams, for example polyolefins, the system comprises:

a charging device for continuous or discontinuous charging feedstock onto a stationary pyrolysis liquid maintained in a molten state at temperatures between 160 and 700°C in an oxygen-devoid atmosphere and operating pressures above atmospheric within a pyrolysis chamber;

at least one pyrolysis vapour removal line to remove the vapour product from said pyrolysis chamber; and

and at least one liquid product drain device to remove the accumulated waxes on said stationary pyrolysis liquid.

Various embodiments of the present invention provide a pyrolysis system for recycling a feedstock composed of mixed or single waste plastic streams, for example, polyolefins, comprising:

a charging device for continuously or discontinuously charging the feedstock into a first of a plurality of pyrolysis chambers 6 arranged in series, the pyrolysis chambers comprising a pyrolysis liquid 7;

one or more vapour removal lines 12 for continuously or discontinuously removing one or more vapour products;

one or more liquid product drains 3 for continuously or discontinuously removing one or more wax products which may be the feed stream for a subsequent pyrolysis chamber;

one or more extractors 35 for continuously or discontinuously removing one or more vapour and solid products in a final pyrolysis chamber 6; and

continuously or discontinuously condensing the vapour products from the plurality of pyrolysis chambers to produce waxes or pyrolysis oils.

In a preferred embodiment of the present invention the system comprises two pyrolysis chambers 6, each comprising a stationary pyrolysis liquid 7 maintained in a molten state at temperatures between 160 and 700°C operating in an oxygen-devoid atmosphere and operating pressures above atmospheric, wherein:

a first pyrolysis chamber 39 comprises one or more vapour removal lines 12 for removing a first vapour product and a liquid product removal drain 3 for removing a first liquid wax product;

feeding the first liquid wax product removed is the feed stream for a second pyrolysis chamber 40; and

the second pyrolysis chamber 40 comprises one or more extractors 35 for removing a vapour and a solid product, and a liquid product drain 3 for removing a second liquid wax product.

In a preferred embodiment of the present invention the second pyrolysis chamber operates at a higher temperature and/or a lower pressure than the first pyrolysis chamber.

In this system, the liquid product drain may be equipped with multiple filters in series with decreasing mesh sizes towards the outlet, preventing plastic pieces that are not fully pyrolysed from exiting the reactor. Moreover, the liquid product may be filtered outside the reactor. The liquid product may be drained continuously or intermittently from the reactor.

The system may comprise multiple liquid product drain devices and multiple pyrolysis vapour removal lines or variations thereof.

The pyrolysis liquid may be a molten non-ferrous metal or alloy consisting of at least one of zinc, tin, indium, lead, aluminium and copper. Molten zinc may, for example, be used.

Where multiple pyrolysis vapour removal lines are installed to remove the product vapours from the pyrolysis chamber, they may be located at similar distances from where the charging device feeds into the pyrolysis chamber.

The system may also comprise an impingement plate above the pyrolysis liquid and below the outlet from the charging device into the pyrolysis chamber. The charging device may, for example, be a screw feeder or an extruder or both.

The pyrolysis chamber may have one or more weirs, which may be fitted with v-notches (Fig. 7) to remove the liquid accumulating on the molten metal.

The molten metal may be heated by a plurality of heat sources, such as burners, below the base plate at different locations. It is desirable to ensure that the temperature stays the same across the surface of the molten metal. This can be achieved by monitoring the temperature of the molten metal at a plurality of spaced-apart locations and controlling the heat sources in response to those temperature measurements. For example, the temperature may be held this way to ensure it varies by no more than 5°C, preferably no more than 2°C, across the width of the pyrolysis chamber. It will be appreciated that the good thermal conductivity of the molten metal and natural convection within the molten metal ensures a substantially uniform temperature across the molten metal surface.

According to a second aspect of the present invention, there is provided a pyrolysis process for recycling a feedstock composed of mixed or single waste plastic streams, for example, polyolefins, the process comprises the steps:

a) continuously or discontinuously charging said feedstock onto said stationary pyrolysis liquid maintained in a molten state at a temperature between 160 to 700°C in an oxygen-devoid atmosphere and an operating pressure above atmospheric within said pyrolysis chamber;
b) continuously or discontinuously removing the vapour product via at least one pyrolysis vapour removal line from said pyrolysis chamber while maintaining an operating pressure above atmospheric within said pyrolysis chamber;

c) continuously or discontinuously removing the wax products from the surface of said pyrolysis liquid via at least one wax drain and, subsequently, from said pyrolysis chamber; and

d) continuously or discontinuously condensing the vapour product to produce waxes or pyrolysis oil.

Various embodiments of the present invention provide a pyrolysis process for recycling a feedstock composed of mixed or single waste plastic streams, for example, polyolefins, comprising the steps of:

continuously or discontinuously charging the feedstock into a first of a plurality of pyrolysis chambers 6, wherein the pyrolysis chambers are arranged in series and comprise a pyrolysis liquid 7;

continuously or discontinuously removing one or more vapour products via one or more vapour removal lines 12;

continuously or discontinuously removing one or more wax products via one or more liquid product drains 3 which may be the feed stream for a subsequent pyrolysis chamber;

continuously or discontinuously removing one or more vapour and solid products via one or more extractors 35 in a final pyrolysis chamber 6; and

continuously or discontinuously condensing the one or more vapour products from the plurality of pyrolysis chambers to produce waxes or pyrolysis oils.

In a preferred embodiment of the present invention the process comprises the steps of:

continuously or discontinuously charging the feedstock into a first of two pyrolysis chambers 39 comprising a stationary pyrolysis liquid 7 maintained in a molten state at temperatures between 160 and 700°C operating in an oxygen-devoid atmosphere and operating pressures above atmospheric;

continuously or discontinuously removing a vapour product from the first pyrolysis chamber 39 via one or more vapour removal lines 12;

continuously or discontinuously removing a wax product from the first pyrolysis chamber 39 via one or more liquid product drains 3 and feeding this to a second pyrolysis chamber 40;

continuously or discontinuously removing the vapour and solid product via one or more extractors 35 in the second final pyrolysis chamber 40; and

continuously or discontinuously condensing the vapour products from the first and second pyrolysis chambers to produce waxes or pyrolysis oils.

In another embodiment there is provided a reactor system for recycling feedstock such as single or mixed plastics, for example polyolefins, comprising a charging device for continuous or discontinuous charging of the feedstock, the system characterised by a plurality of pyrolysis chambers arranged in series, wherein at least one or each pyrolysis chamber comprises:

a pyrolysis liquid selected from one or more pyrolysis liquids;

one or more vapour removal lines;

one or more liquid product drains; and

one or more vapour and solid product extractors,

wherein a liquid wax phase generated in a pyrolysis chamber is the feedstock stream for the subsequent chamber.

In a further embodiment there is provided a method for recycling feedstock such as single or mixed plastics, for example polyolefins, comprising the steps of:

arranging a charging device for continuous or discontinuous charging of the feedstock;

positioning a plurality of pyrolysis chambers in series;

generating a liquid wax in a pyrolysis chamber to provide the feedstock stream for a subsequent chamber; and wherein at least one or each pyrolysis chamber comprises: a pyrolysis liquid selected from one or more pyrolysis liquids; one or more vapour removal lines; one or more liquid product drains; and one or more vapour and solid product extractors.

Brief Description of the Drawings

The characteristics and advantageous characteristics of the present invention are detailed in this section based on the accompanying drawings in a non-restrictive feedstock example: pure HDPE plastic recycling with reference to the attached drawings wherein:

Fig. 1 is a partial cross-sectional view of one embodiment of pyrolysis chamber (6) with several screw feeder(s) (18) on the side of pyrolysis chamber (6).

Fig. 2 is a cross-sectional view of section A-A (Fig. 1), showing two options for how feedstock (1) may be distributed within pyrolysis chamber (6). Fig. 2A shows multiples feed screws (20) and associated completely separated sections of the pyrolysis chamber (6). Fig. b shows a single feed screw (20) and partially separated sections of the pyrolysis chamber (6).

Fig. 3 is a partial cross-sectional view of one embodiment of pyrolysis chamber (6) where screw feeder (18) is located on top of pyrolysis chamber (6) and pyrolysis vapour removal line(s) (12) are located in the four corners of pyrolysis chamber (6).

Fig. 4 is a view of section K-K as indicated in Fig. 3; also shown is the direction of travel of feedstock (2) to four pyrolysis vapour removal line(s) (12) located in each corner of pyrolysis chamber (6) while the liquid product is directed towards, for example, two liquid product drain(s) (3), located between two pyrolysis vapour removal line(s) (12).

Fig. 5 is a cross-sectional view of one embodiment of pyrolysis chamber (6) equipped with weir (21), ensuring a constant level of liquid product on pyrolysis liquid (7) and directing the liquid product towards liquid product drain (3).

Fig. 6 is a partial cross-sectional view of one embodiment of pyrolysis chamber (6) equipped with a rotary valve (25) as the charging device of feedstock 1.

Fig. 7 is a view of one embodiment of weir (21) with several V-notches to facilitate draining the liquid from pyrolysis liquid 7.

Fig. 8 is a cross-sectional view of one embodiment of liquid product drain (3) equipped, for example, with two mesh filters (4) with decreasing mesh sizes towards liquid product drain (3).

Fig. 9 is a cross-sectional view of one embodiment of pyrolysis chamber (6) as a cascade reactor system where the product from one reactor is the feed for the next reactor.

Fig. 10 is a cross-sectional view of one embodiment of pyrolysis chamber (6) where the liquid product drain (3) is equipped, for example, with two mesh filter(s) (4) with decreasing mesh sizes towards liquid product drain (3) and a chicane system (34).

Note that for clarity, not all features of the invention are shown on all drawings.

<u>Drawings Legend</u>

1. Feedstock
2. Direction of travel of feedstock
3. Liquid product drain
4. Mesh filter
5. Pyrolysis chamber top wall
6. Pyrolysis chamber
7. Pyrolysis liquid
8. Burner
9. Pyrolysis chamber sidewall
10. Pyrolysis chamber bottom wall
11. Feedstock within the pyrolysis chamber
12. Pyrolysis vapour removal line
13. Condenser system
14. Fan
15. Non-condensable line
16. Pyrolysis oil
17. Feedstock hopper
18. Charging device; here: Screw feeder
19. Screw of screw feeder

20. Screw feeder motor
21. Weir
22. Flange for screw feeder
23. Separation wall
24. Impingement plate
25. Charging device; here: Inlet rotary valve
26. Pyrolysis liquid drain
27. Pyrolysis oil return line
28. Product stream 1
29. Product stream 2
30. Connection conduit
31. Product stream 3
32. Product stream 4
33. Chicane wall section
34. Chicane
35. Extractor
36. Cyclone
37. Cyclone rotary valve
38. Solids removal line
39. First pyrolysis chamber
40. Second pyrolysis chamber

<u>Detailed Description</u>

The pyrolysis liquid (7) may be a molten metal. Zinc, tin or alloys thereof are most desirable. Zinc melts at 419°C, boils at 905°C and is relatively inexpensive compared to many other metals. Tin is also desirable as it melts at 231.9°C and boils at 2,602°C. The molten metal is the heat transfer medium and is not consumed by the process. Using indium as the molten metal, operating temperatures as low as 156.6°C (melting point of indium) may be achieved. However, in practice, the actual operating point will be at least 5-10°C higher than the melting point of the molten metal. In the examples below, the pyrolysis liquid (7) is molten zinc, held at 450°C by burner(s) (8).

Example: Pure plastics

The objective of pure or single plastic treatment with the present invention is to recover pyrolysis oil, waxes, or basic chemicals.

In one embodiment, single plastic waste or feedstock (1) is added from above a pyrolysis chamber (6) (Fig. 3) onto the middle of pyrolysis chamber (6), i.e., at substantially equal distances from the pyrolysis vapour removal line(s) (12). An impingement plate (24) may be added to pyrolysis chamber (6) to avoid molten metal or wax splashes within pyrolysis chamber (6) caused by feedstock (1) addition. The pyrolysis vapours are removed from pyrolysis chamber (6) via pyrolysis vapour removal line(s) (12). The pyrolysis vapours are condensed by condenser system (13) to pyrolysis oil (16). Fan (14) provides the required suction for the pyrolysis vapour removal operation. The non-condensables line (15) carries the pyrolysis gases or the non-condensables such as methane, propane, and other gases, which may be sent to burner(s) (8) to heat the pyrolysis process making it self-sustaining, or the gases may be used to generate electricity or both.

Example: Mixed and pure plastics

The objective of mixed and pure plastic treatment with the present invention is to recover pyrolysis oil, waxes, or basic chemicals.

In another embodiment shown in Fig. 9, two pyrolysis chamber(s) 6 are arranged in a reactor cascade, where one reactor feeds the one below by gravity. The waste plastic, be it pure or mixed plastics or feedstock (1), is added to the first pyrolysis chamber (39). The plastic is pyrolysed into volatiles and a liquid wax phase, accumulating on pyrolysis liquid (7). The volatiles including contaminants such as water exit the first pyrolysis chamber (39), and these vapours may be condensed by condenser system (13) to product stream 1 (28), whereas the non-condensables are removed via non-condensable line (15). The liquid wax phase accumulating on pyrolysis liquid (7) in the first pyrolysis chamber (39) overflows and flows by gravity via connection conduit (30) to the second pyrolysis chamber (40) or is in part or whole recovered as product stream 2 (29). The second pyrolysis chamber (40) operates at a higher temperature than the first (39). Due to the higher operating temperature, the liquid wax phase, i.e. the feedstream to the second pyrolysis chamber (40), cracks into pyrolysis vapours and pyrolysis solids. The pyrolysis solids, for example, carbon, either generated by the cracking process or present in the feed stream, accumulate in the second pyrolysis chamber (40) above pyrolysis liquid (7). The products from the second pyrolysis chamber (40) are either product stream 3 (31), i.e. a liquid wax phase, or product stream 4 (32), which is a condensed stream generated from the pyrolysis vapours originating in the second pyrolysis chamber (40). The first pyrolysis chamber (39) and second pyrolysis chamber (40), shown in Fig. 9, are for illustrative purposes. Moreover, the first pyrolysis chamber (39) and the second pyrolysis chamber (40) may not be similar in size or shape. Any number of pyrolysis chambers can be used.

In another embodiment (Fig. 9), an extractor (35) is used to remove the pyrolysis vapours and the solids accumulating on top of the pyrolysis liquid (7) at the same time.

In another embodiment (Fig. 1), one or more charging device(s) (18) and associated equipment are located on the pyrolysis chamber side wall (9). The removal of the pyrolysis vapours from pyrolysis chamber (6) is accomplished by pyrolysis vapour removal line(s) (12). The pyrolysis vapours are condensed by condenser system (13) to pyrolysis oil (16). Fan (14) provides the required suction for the vapour removal operation. The non-condensable line (15) includes methane, propane and other gases, which may be sent to burner(s) (8) to heat the pyrolysis process, making it self-sustaining. The non-condensable gases may be used to generate electricity or for other uses or combinations thereof.

In another embodiment (Fig. 2, option A or option B), pyrolysis chamber (6) is split into lanes or sections by one or more separation wall(s) (23). Separation wall (23) ensures that feedstock 1 within pyrolysis chamber (6) moves along the surface of pyrolysis liquid (7) in a defined manner. Option A feeds every lane by a charging device (18). The pyrolysis vapours are removed by a dedicated pyrolysis vapour removal line (12), located at the end of the line. In option B, one screw feeder (18) feeds more than one lane, each equipped with one pyrolysis vapour removal line (12).

A pyrolysis oil return line (27) may be added to recycle part or all of the pyrolysis oil 16 to pyrolysis chamber (6) for further cracking the waxes into oils or gases.

Pyrolysis liquid drain (26), shown in Fig. 3, may be added to pyrolysis chamber (6) to remove pyrolysis liquid (7).

Liquid product drain 3, shown in Figs. 1, 2, 3, 4, 5, 8, 9 and 10 remove the liquid product, e.g. long-chain waxes from pyrolysis chamber (6).

In another embodiment (Fig. 10), a chicane (34) is added to the pyrolysis chamber (6), ensuring a sufficient residence time for volatiles present in the accumulated liquid wax phase to evaporate.

In another embodiment, the pyrolysis liquid (7) is heated by electrical heating elements.

Catalysts may be added to pyrolysis chamber (6) to facilitate the cracking of the plastic or the waxes to lighter molecules.

A desirable characteristic of the present invention is that non-condensable gases such as methane or propane may be routed to the burner(s), minimising the energy requirements of the process.

Another desirable characteristic of the present invention is that the pyrolysis vapours may be condensed to pyrolysis oil, pyrolysis waxes or both, for example, by providing a plurality of condenser systems in series; there might, for example, be four condenser systems in series arranged to produce liquid phases at 150°C, 80°C, 45°C and 20°C.

Another desirable characteristic of the present invention is that the pyrolysis process is fast, as the heat transfer is done directly by heating the waste material with molten metal or molten salt.

Another desirable characteristic of the present invention is that the pyrolysis process is readily scalable, as doubling the surface area of pyrolysis liquid (7) doubles throughput.

Another desirable characteristic of the present invention is that the high boilers accumulate on top of the molten metal as a liquid and do not need to be evaporated or cracked further for recovery; savings on energy are realised. Energy is also saved as the material does not need to be condensed. Instead, they can be continuously or intermittently drained from the pyrolysis chamber.

Another desirable characteristic of the present invention is that surface crusts, which frequently form on the surfaces of fixed wall pyrolysis reactors, are avoided as the pyrolysis liquid is a liquid, i.e., not a solid wall. Moreover, molten zinc, tin and similar metals repel carbon, glass, and similar materials.

Another desirable characteristic of the present invention is the ability to treat mixed plastics, i.e., a waste stream composed of different types of plastics. This is important, as obtaining a plastic waste stream from municipal waste composed only of one kind of plastic is challenging. Moreover, this invention can also treat plastics contaminated with foreign materials, e.g., plastic packaging with food residues, paper, ink, and other contaminants.

Definitions

"Mixed plastics" refers to a waste plastic stream composed of various types of plastics mixed, e.g., polyethylene (PE), polypropylene (PP), low-density polyethylene (LDPE), high-density polyethylene (HDPE), polyvinyl chloride (PVC), polystyrene (PS), etc.

"Pure plastics" refers to a waste plastic stream composed of a single type of plastic such as PE, PP, LDPE, HDPE, PVC or PS.

"Polyolefin" refers to a waste plastic stream composed of polymers produced from a simple olefin as a monomer — for example, PE, PP, LDPE, and HDPE as pure or mixed streams.

In the specification the terms "comprise, comprises, comprised and comprising" or any variation thereof and the terms include, includes, included and including" or any variation thereof are considered to be totally interchangeable and they should all be afforded the widest possible interpretation and vice versa.

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

Claims

1. A reactor system for recycling feedstock (1) such as single or mixed plastics, for example polyolefins, comprising a charging device for continuous or discontinuous charging of the feedstock, the system characterised by a plurality of pyrolysis chambers (6) arranged in series, wherein each pyrolysis chamber (6) comprises:

a pyrolysis liquid (7) selected from one or more pyrolysis liquids;

one or more vapour removal lines (12);

one or more liquid product drains (3); and

one or more vapour and solid product extractors (35),

wherein a liquid wax phase generated in a pyrolysis chamber (6) is the feedstock stream for a subsequent chamber (6).

2. A reactor system as according to claim 1 wherein the plurality of pyrolysis chambers (6) comprises a first pyrolysis chamber (39) and a second pyrolysis chamber (40), wherein the first pyrolysis chamber is held at a higher than atmospheric pressure, the system comprising:

a first pyrolysis liquid (7) held at a temperature from 160 to 700°C, comprising a stationary, continuous, fluidic molten surface on which the feedstock (1) is separated into a first liquid wax phase and a first vapour pyrolysis product;

one or more vapour removal lines (12) for removing the first vapour product; and

one or more liquid product drains (3) for removing the first liquid wax phase from the first pyrolysis chamber (39) and feeding the liquid wax phase to the second pyrolysis chamber (40) via a connection conduit (30), wherein the second pyrolysis chamber (40) is held at a pressure lower than the first pyrolysis chamber and comprises:

a second pyrolysis liquid (7) at a temperature from 160 to 700°C and higher than the temperature of the first pyrolysis liquid on which the first liquid wax phase is separated into a combination of a second liquid wax phase, a second vapour pyrolysis product, and a solid pyrolysis product; and one or more extractors (35) for the removal of the second vapour pyrolysis product and the solid pyrolysis product.

3. A system according to claim 2, characterised in that the second pyrolysis chamber (40) is equipped with one or more additional liquid product drains (3).

4. A system according to any preceding claim, wherein one or more of the plurality of pyrolysis chambers (6) are equipped with a chicane (34), wherein the chicane (34) is comprised of at least one chicane wall section (33).

5. A system according to any preceding claim wherein one or more of the vapour and solid product extractors (35) comprises a lance or other extractor mechanism.

6. A system according to any preceding claim wherein pyrolysis vapours and solid pyrolysis products extracted by the one or more vapour and solid product extractors are separated in a cyclone (36).

7. A system according to any preceding claim characterised in that a catalyst, for example, ZnO or Al_2O_3, is present on the surface of one or more of the pyrolysis liquids (7).

8. A system according to any preceding claim characterised in that one or more of the plurality of pyrolysis chambers (6) are equipped with a weir (21).

9. A system according to any preceding claim characterised in that one or more of the plurality of pyrolysis chambers (6) further comprise one or more mesh filters (4) upstream of the one or more liquid product drains.

10. A system according to any preceding claim characterised in that one or more of the pyrolysis liquids (7) are a molten non-ferrous metal and selected from at least one of zinc, tin, lead, aluminium, indium, copper, or alloys thereof

or is a molten salt selected from LiCl, KCl, KOH, NaOH, cyanides, nitrates, nitrites or combinations thereof.

11. A system according to any preceding claim characterised in that no extractors (35), weirs (21), chicanes (34), second pyrolysis chambers (40), connection conduits (30), liquid product drains (3), or combinations thereof are installed.

12. A method for recycling feedstock (1) composed of materials such as mixed plastics, but also single waste plastic streams such as polyolefins, the method comprising the steps of:

charging said feedstock (1) by a charging device (18,25), said charging device (18,25) adapted to remove air from said feedstock (1);

charging said feedstock (1) from said charging device (18,25) into a first pyrolysis chamber (39) comprised of a pyrolysis liquid (7) which is a stationary fluid held at a temperature from 160 to 700 °C, and comprises a continuous, fluidic molten surface on which said feedstock (1) separates into any or all of a vapour pyrolysis product, a liquid wax phase and a solid pyrolysis product;

operating a second pyrolysis chamber (40) at a higher temperature than said first pyrolysis chamber (39);

operating said second pyrolysis chamber (40) at a lower pressure than said first pyrolysis chamber (39);

removing said vapour pyrolysis product via pyrolysis vapour removal line (12) from said first pyrolysis chamber (39);

removing said vapour pyrolysis product via one or more pyrolysis vapour removal lines (12) from said second pyrolysis chamber (40); and

removing said solid product via one or more solid pyrolysis extractors (35) from the surface of said pyrolysis liquid (7) located in said second pyrolysis chamber (40).

13. A method for recycling feedstock such as single or mixed plastics, for example polyolefins, comprising the steps of:

arranging a charging device for continuous or discontinuous charging of the feedstock;

positioning a plurality of pyrolysis chambers in series;

generating a liquid wax in a pyrolysis chamber to provide the feedstock stream for a subsequent chamber; and wherein at least one or each pyrolysis chamber comprises: a pyrolysis liquid selected from one or more pyrolysis liquids; one or more vapour removal lines; one or more liquid product drains; and one or more vapour and solid product extractors.

14. A reactor cascade system for recycling feedstock (1) comprising materials such as mixed or single plastics, for example polyolefins, the system comprising:

two pyrolysis chambers (6) arranged in series, wherein a liquid wax phase generated in a first pyrolysis chamber (39) is the feed stream for a second pyrolysis chamber (40), arranged in such a way that said liquid wax phase flows by gravity via connection conduit (30) from said first pyrolysis chamber (39) to said second pyrolysis chamber (40);

a charging device (18) configured to charge said feedstock (1) to the first pyrolysis chamber (39) adapted to remove air from said feedstock (1);two pyrolysis liquids (7) contained in said two pyrolysis chambers (6) respectively, held at a temperature from 160 to 700°C, comprising stationary continuous, fluidic (molten) surfaces on which the feedstock (1) is separated into any or all of a liquid wax phase, a solid pyrolysis product, and a vapour pyrolysis product;

one or more pyrolysis vapour removal line (12) configured to remove said vapour pyrolysis product from said first pyrolysis chamber (39);

one or more liquid product drains (3) configured to remove said liquid wax phase with liquid product drain (3) from the surface of a first pyrolysis liquid (7) in said first pyrolysis chamber (39); and

one or more extractors configured to remove said vapour pyrolysis product and said solid pyrolysis product with extractor (35) from the surface of a second pyrolysis liquid (7) in said second pyrolysis chamber (40).

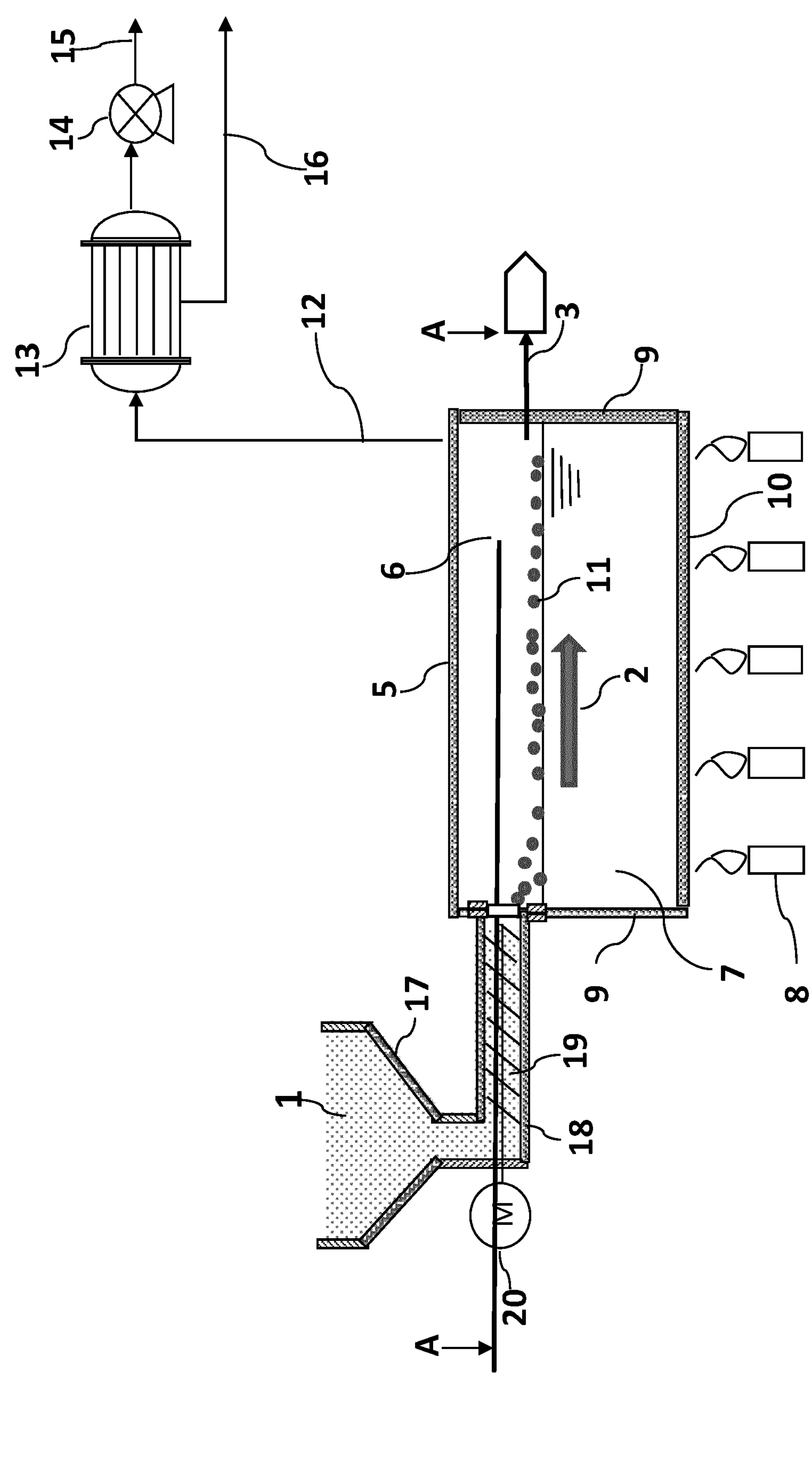

Fig.1

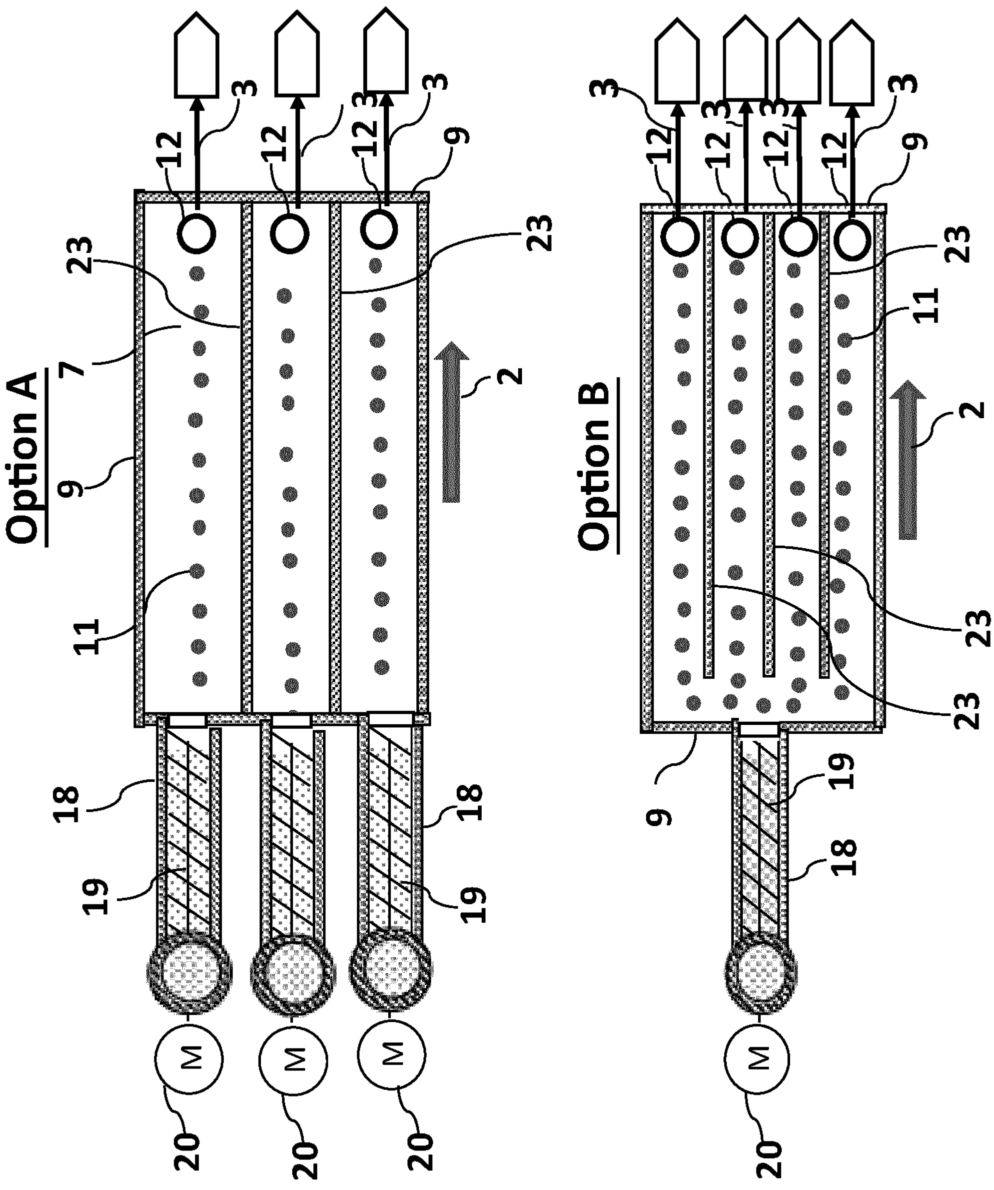

Fig.2 –View A-A of Fig.1&9

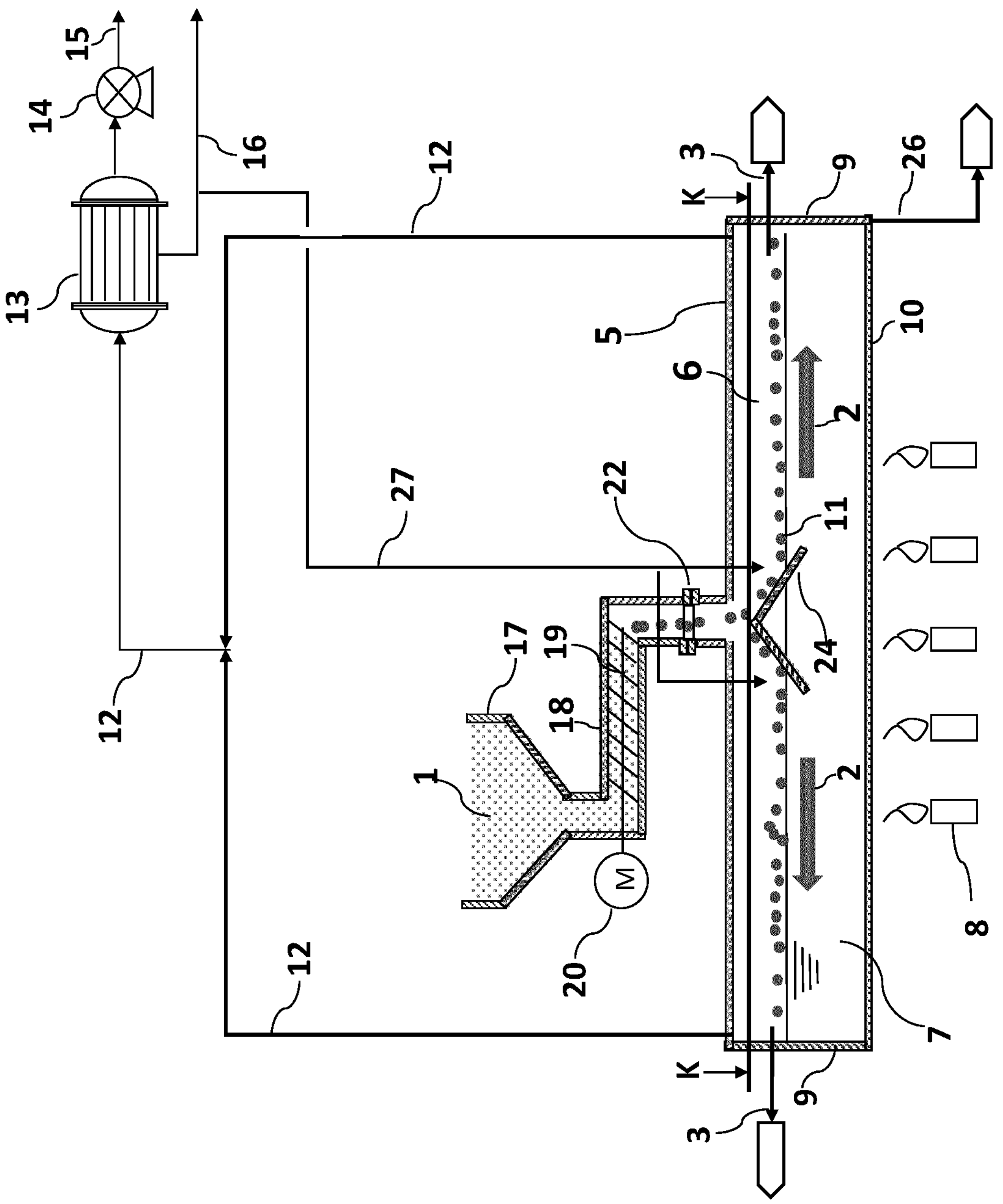
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Fig.3

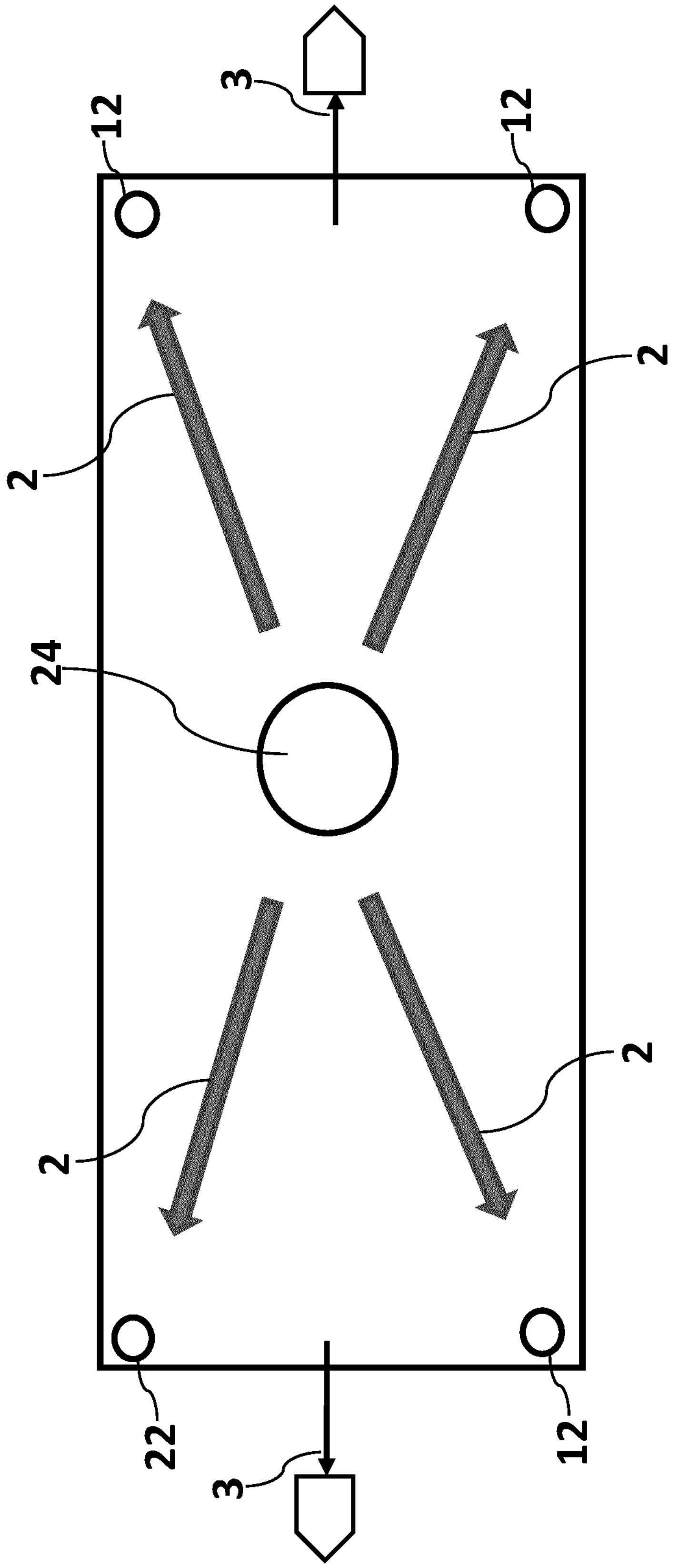


Fig.4 view K-K of Fig.3

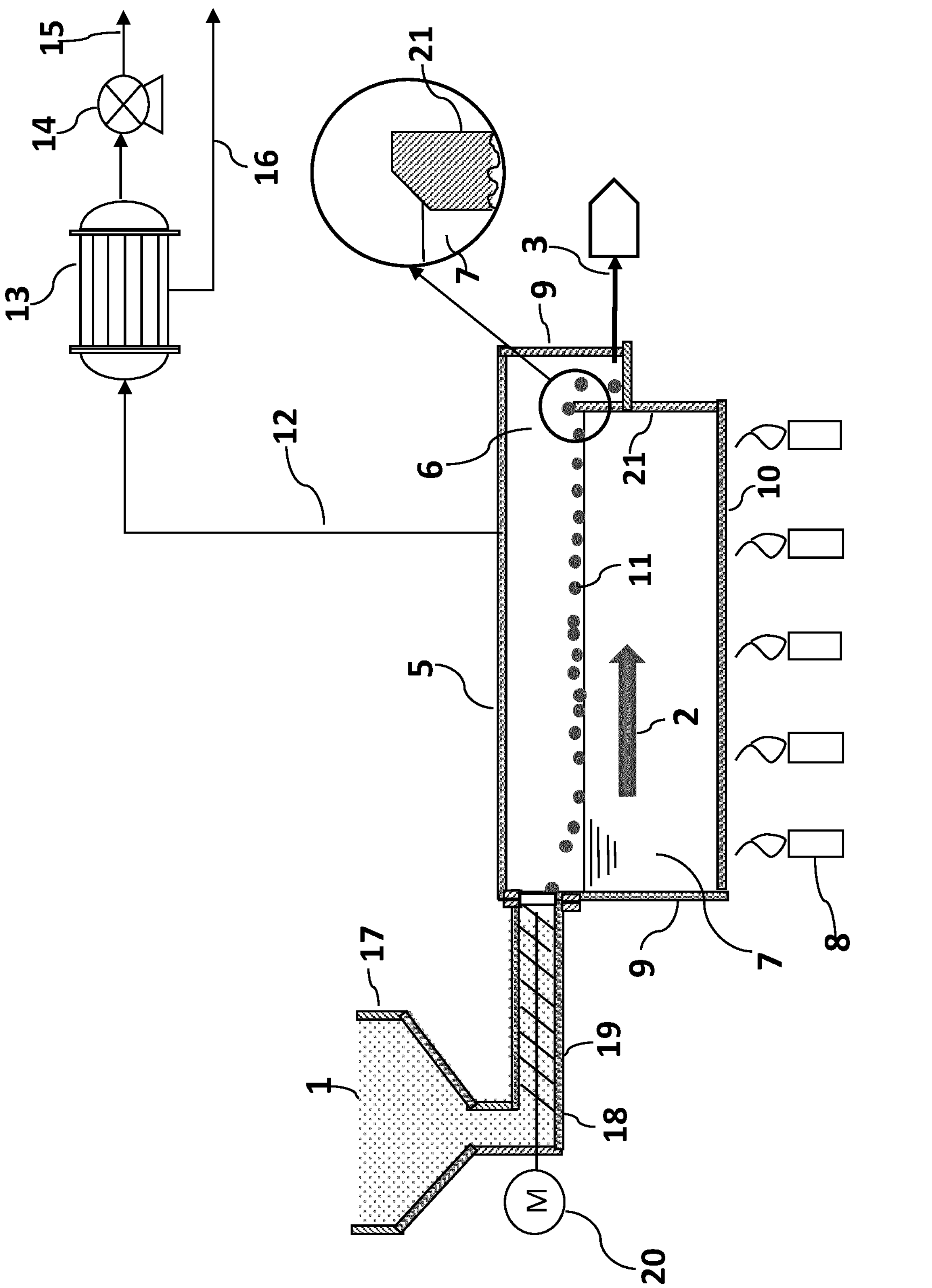


Fig.5

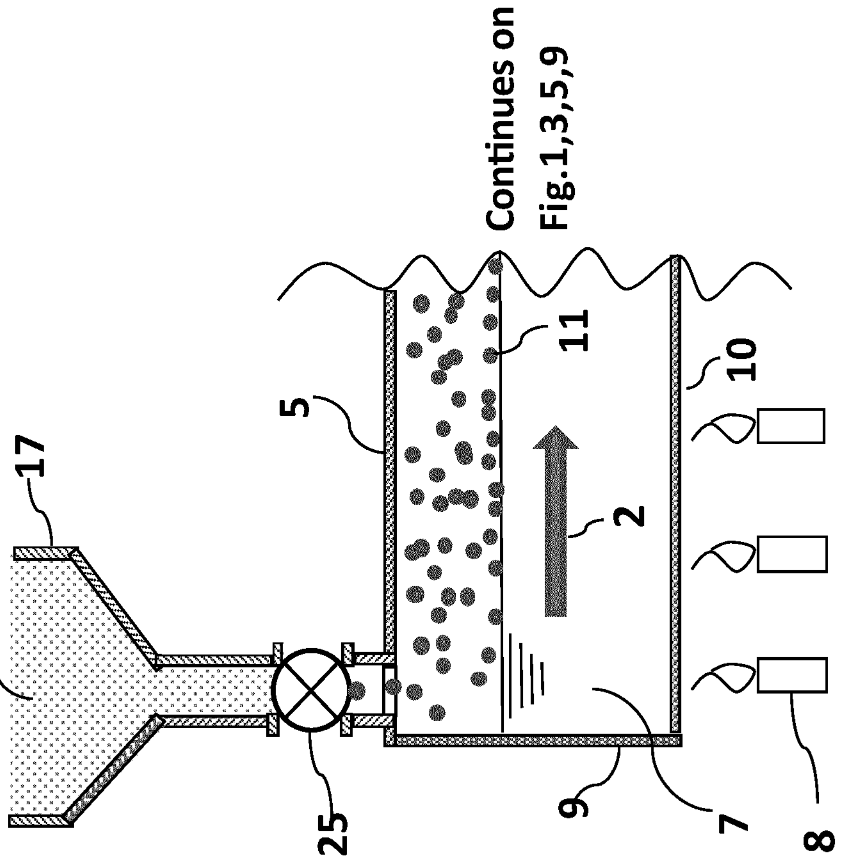


Fig.6

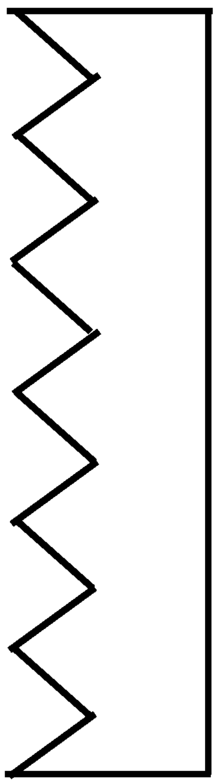
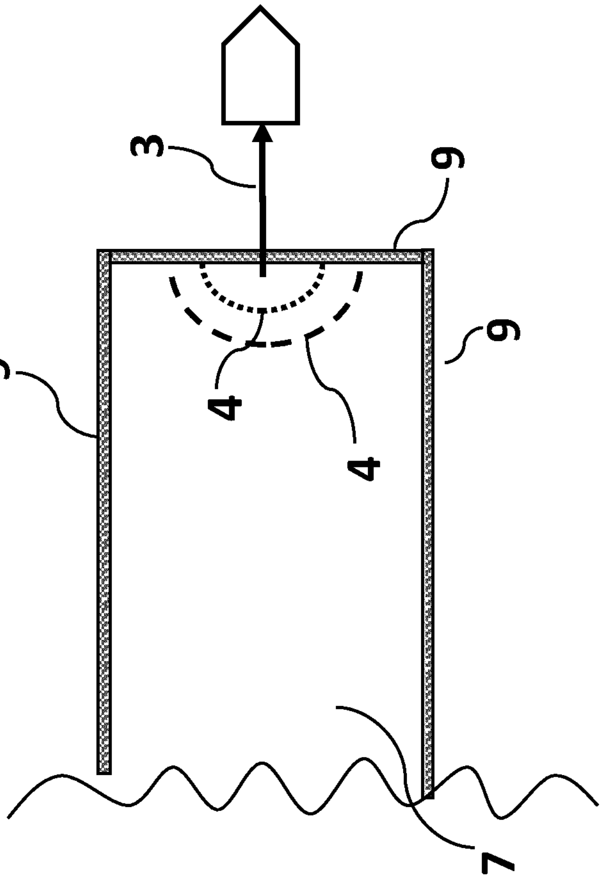


Fig.7



Continues on Fig.2,4

Fig.8

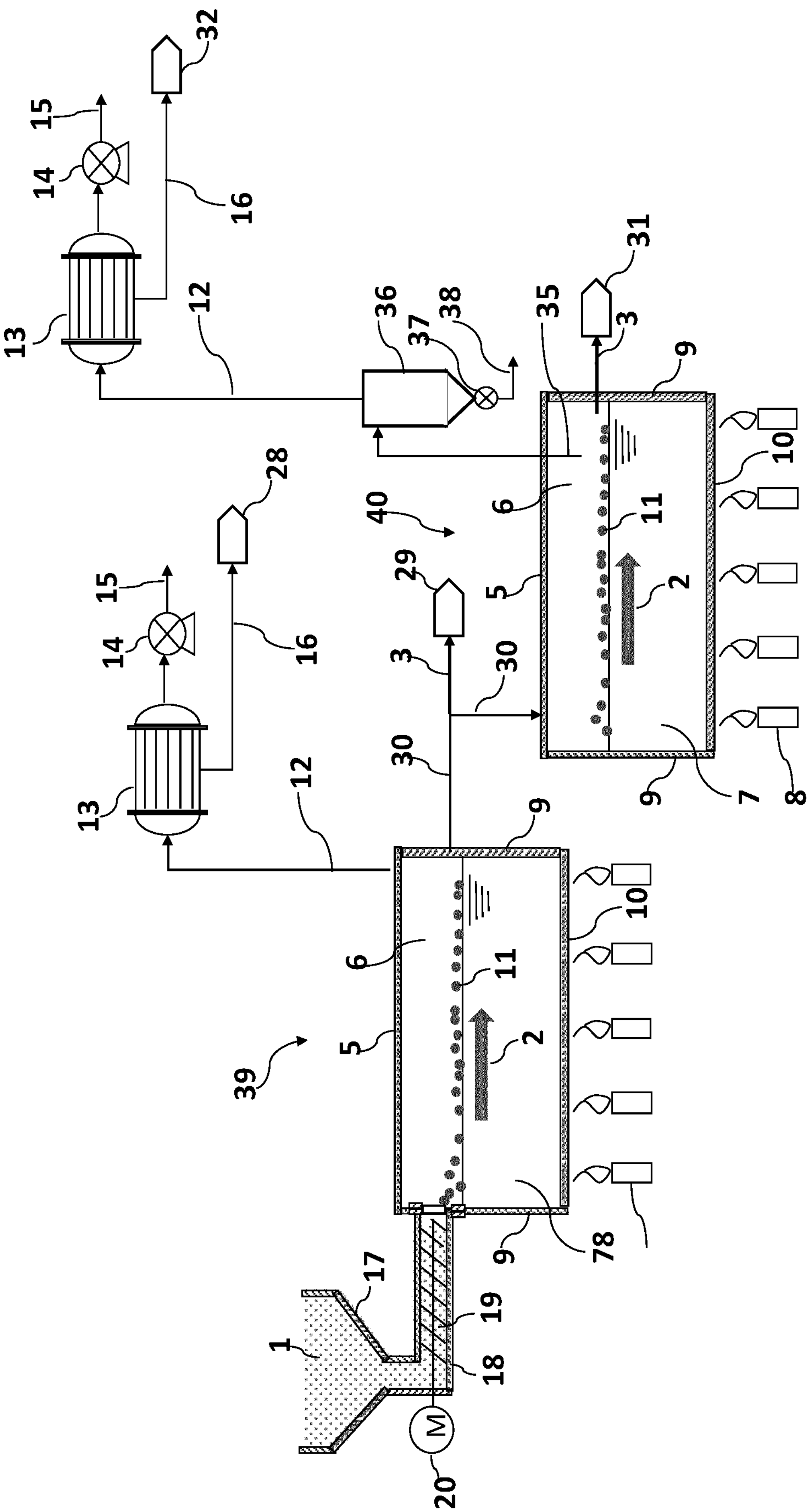

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Fig.9

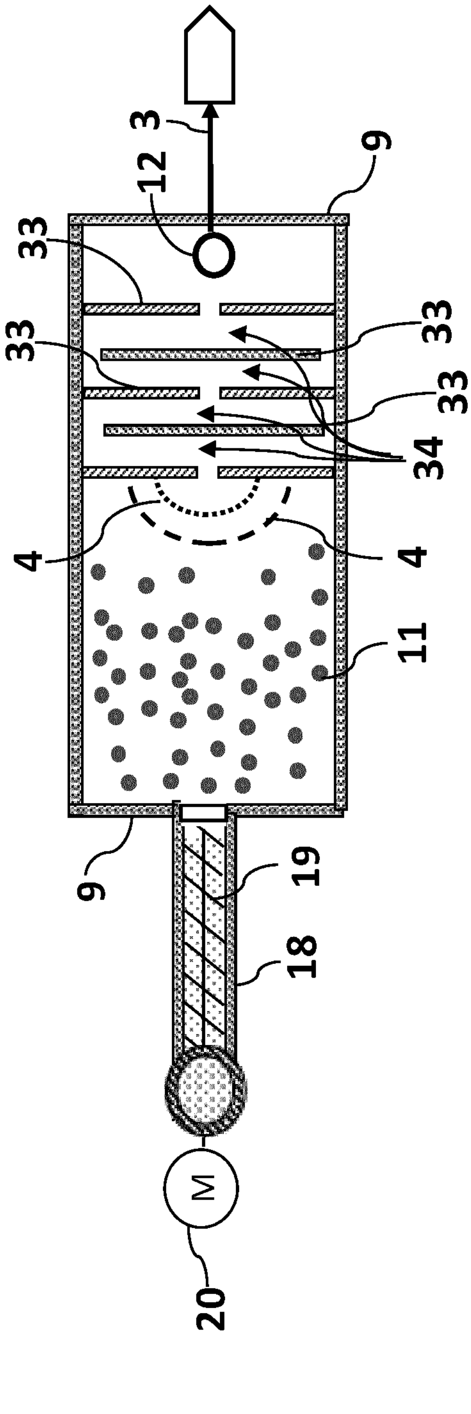

Fig.10