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(54) Title: METHOD OF ELECTRICITY PRODUCTION THROUGH TYRE PYROLYSIS

(57) Abstract: The recycling of vehicle tyres at the end of their life cycle is a universal problem and many processes have been developed to deal with this problem including the process of pyrolysis which involves the thermochemical decomposition of rubber at elevated temperatures. Several problems are believed to hinder the technical and commercial pyrolysis systems most importantly the problems encountered in downstream processes for handling the pyrolysis products as well as the problems encountered with environmental factors. So far no one pyrolysis system is known to be suitable for producing products having industrial i.e. commercial applicability and without producing waste by-products. Thus, although there is extensive literature as well as several patent disclosures relating to systems or processes for decomposing waste vehicle tyres by thermal pyrolysis producing oils and other by-products, none of them refers to the industrial applicability of the Tyre Pyrolysis Oil (TPO) and, in particular, the use of the TPO as fuel for the production of electricity on a commercial scale utilising internal combustion engines within the same premises thereby not having to dispose waste by-product outside the plant boundaries. A number of existing pyrolysis plants throughout the world produce a Tyre Pyrolysis Oil (TPO) which is considered to be a waste by-product and it has to be handled as such. The proposed system, which is the subject of this patent application, is based on the overall concept of putting several unit processes together to produce electrical power, which is the target end product right from the waste tyres within the same premises and therefore avoiding any waste product leaving the premises. The system consists basically of several unit processes which are utilised to achieve three main objectives i.e., a) Producing TPO, Carbon Black (CB) and scrap steel wire products of specific quality standards for eligible industrial uses, b) Upgrading the pyrolysis oil to a quality standard suitable for combustion as fuel in power generating engines of the Internal Combustion Engine (ICE) type producing electrical power as the main target end product on a commercial scale, c) Gaseous emissions with no adverse impacts to the environment thus complying to all environmental laws and regulations applicable anywhere It is also noted that the proposed system does not require any external sources of energy and it is self-sustainable once it has been placed into operation.

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DETAILED DESCRIPTION

The invention, which is the subject of this patent application, relates to a system for the production of electricity as the main target end product from the thermal pyrolysis of vehicle tyres 'at the end of their life cycle' otherwise termed 'waste tyres'.

In the proposed system the pyrolysis process is a thermal process whereby vehicle tyres 'at the end of their life cycle' are thermally decomposed in a heated steel chamber termed 'the pyrolysis reactor' to produce three commercial products namely,

1. TPO (Tyre Pyrolysis Oil) which is a liquid fuel
2. Carbon Black (CB) in powder form and/or in pellets
3. Steel wire, in the form of small pieces compressed into bales

A fourth by-product is the non-condensable HC (Hydrocarbon) gas, otherwise termed 'Syngas' which is used as a gaseous fuel for the in-plant heating requirements.

The pyrolysis reactor can be of any type: rotary kiln, fluid bed vertical or horizontal, or a static chamber with mechanical means of moving the material inside the reactor chamber. In the preferred application described herein the reactor is of the latter type.

The liquid Tyre Pyrolysis Oil (TPO) is further treated in a downstream plant comprising a distillation unit and other separation systems for upgrading it to make it suitable for combustion in a downstream power generation plant to produce electricity.

The various unit processes comprising the invention are described as follows:

The used waste tires are received in bulk, cut into small pieces of typical size 5cm x 5cm, with the steel wire remaining inside the rubber pieces and they are stored in bulk in the warehouse. Alternatively, the tyres are shredded and cut into small pieces on site. As an option, a tyre pieces granulation-washing-drying line may be installed upstream the pyrolysis reactor. In this system, the tyre pieces of typical size 5cm x 5cm are granulated and reduced further in size down to less than 3 mm. The granulate is then washed and dried before feeding to the pyrolysis reactor. In the granulation process the steel wire pieces and the fabric pieces are liberated and mostly (more than 95%) removed by screening and/or magnetic separation and air separation processes respectively. The preferred application described herein incorporates such systems as shown in Fig.4. This has the advantages of,

a) Resulting in better quality CB

b) Increased productivity because of better heat transfer, hence reduced residence time in the pyrolysis reactor

The specific pyrolysis reactor of the preferred application may be operated in batch or continuous mode and in the specific application described herein the continuous mode of operation is utilised.

In the first start-up, the pyrolysis process starts by starting up the drive of the rotary pyrolysis reactor chamber (100) and at the same time the tyre feed system which in this specific application comprises a bucket elevator (101), chain conveyor (102) and screw feeder (103) all in series, is started up and mechanically feeds the cut tyres into the rotating reactor as shown in the Process Flow Diagram, Fig.1. The tyre granulate is moved inside the pyrolysis reactor from front-to-end by mechanical means e.g. a series of paddles as exemplified in the preferred application described herein, so as to achieve uniformity of the mixture and uniform heat transfer. Heating is applied by circulating FG (Flue Gas) from a downstream waste incinerator (109) through the peripheral jacket of the reactor and the reactor begins to heat up. The pyrolysis temperature is controlled in accordance to the predetermined temperature-time profile which has been set in the DCS (Digital Control System) system. Typically, the temperature gradient is fast at the beginning up to 180^{0}C, it is then decreased slightly to go slower to the final pyrolysis temperature in the range of 400-500 ^{0}C. It is then held at this final temperature whilst the reactor is fed with tyre granulate continuously at a steady rate. At the same time, the CB and the remaining Steel wire pieces are discharged from the outlet at the other end of the reactor chamber by mechanical systems, and more specifically in this preferred application, by closed chain conveyor (201) as shown in the Process Flow Diagram, Fig.2 .

Gaseous hydrocarbons begin to emerge from the pyrolysis reactor at a temperature around 150 ^{0}C and directed via a separation pot (104) to take out the impurities and / or heavy fractions (tar), to the water cooled condensers (105) of the vertical shell-and-tube type whereby they are condensed by cooling and liquefied into liquid product i.e. raw Tyre Pyrolysis Oil (TPO) which is collected in a buffer storage vessel (106) as shown in the Process Flow Diagram, Fig.1.

The system of condensers comprising multiple condensers arranged in parallel and/or in series, or any combination of the two, whereby the condensable fraction of the Hydrocarbon (HC) gas coming from the pyrolysis reactor chamber is condensed into liquid TPO and collected in a buffer tank as mixed product or in different buffer tanks as separate liquid products of differing composition thus segregating the fraction containing furans which are toxic pollutants. This ensures the elimination or at least minimising the presence of toxic pollutants in the gaseous emissions from the downstream power plant. The contaminated fraction of liquid TPO may be mixed with the fraction of TPO burned in the waste incinerator.

The non-condensable HC (Hydrocarbon) Gases are collected in a buffer tank (107). From this tank the Syngas is fed to a Gas Turbine generator producing electricity as shown in the Process Flow Diagram, Fig.1. If there is a need for additional heating requirements in other plant units, a portion of the Syngas may be burned in the waste incinerator producing additional FG for heating purposes.

All heating requirements will be effected by directing Flue Gas (FG) at 850°C arising from the combustion of the excess Syngas (Non-condensable Hydrocarbon Gas) and/or the off-grade fractions of TPO, resulting from the distillation of raw TPO, in a special combustion chamber (109) used to incinerate all plant solid and/or liquid wastes, to the pyrolysis reactor jacket. Only for the very first batch some Light Fuel Oil (LFO) will be used drawn from the on-site LFO storage tank (108). The FG from the pyrolysis reactors is mixed with other FG streams coming from the waste incinerator (109) and from the furnace of the distillation plant (302 in Fig.3) in a mixing manifold (111) prior to going through the FG treatment section and to the exit stack (117).

In the plant which is the subject of this application a multiple number of pyrolysis reactors, in this specific example 6 reactor lines, shall be used. Apart from achieving higher production rates thus achieving economies of scale, the use of multiple reactors which can be started up sequentially and phased out by a set time interval, serves to smooth out the peaks in the evolution of the HC gas and accordingly the use of the non-condensable syngas. Thus the cycle in the second reactor will start about 4 hours after starting the first reactor, the cycle in the third reactor will start about 4 hours after the second and so forth. The starting up and loading of the reactors sequentially at pre-determined time intervals can be controlled by the DCS (Digital Control System).

The mixture of CB (Carbon Black) and steel wires is discharged and mechanically transported by chain conveyor (201) and fed to a downstream cooling screw conveyor (202) which in turn feeds the downstream vibratory screen (203) which separates the CB-Steel wire mixture as shown in Fig.2. The steel wire is fed into the press (207) which compacts the wire pieces into 1-ton bales whereas the CB and any remaining steel pieces are collected in an intermediate storage silo (204). From the silo the mixture is fed to a magnetic separator (205) which removes any remaining steel wire pieces from the CB powder. The steel wire pieces are transported to the press (207) whereas the coarse CB powder is transported by means of a cooling screw conveyor (206) into a storage silo (208). From this silo, the coarse carbon black powder is fed into a rotary mill (209) for milling to a fine carbon black powder which is collected in a buffer hopper (210) as shown in Fig.2. The CB powder is then fed to a pelletizing machine (213), preferably of the extruder type, in which water is injected by means of a metering pump (212) and the CB powder is transformed into spherical pellets of size ≤1,0 mm. The CB pellets are then dried completely in a FBD (Fluid Bed Dryer) (214) or rotary kiln dryer and after cooling they are collected in an intermediate storage silo (215). From this silo the CB pellets are fed to a packing system where they are packaged in 1-ton bulk bags and/or 25kg bags as shown in Fig.2.

Typical yields from the pyrolysis process are as follows

TPO (Tyre Pyrolysis Oil)	42-45
CB (Carbon Black)	30-35

Steel wires	12-15
Non-condensable syngas	8-10

The raw TPO fuel oil from the pyrolysis plant is pumped to storage tanks for further processing in the Distillation Unit whereby it is refined and upgraded to meet a specification better than LFO (Light Fuel Oil) or even closer to the specification of Diesel for ICE (Internal Combustion Engines). Most typically it is upgraded by removing the light fractions (typically 10%) and the heavy fraction (3-5%) in the distillation unit and then by a series of purification steps including centrifugation and fine filtration to remove any residual water and solid impurities.

The distillation unit may be of a simple design comprising basically one "Distillation Tower" (a distillation kettle with elevated column) which has 3 sections operated at a temperature gradient from bottom to top typically 380-400 °C at the bottom and 150-180 °C at the top so as to separate the raw TPO into the desired 3 fractions of which the middle fraction is the desired fuel for power generation. The raw TPO is fed from the storage tank (301) to the bottom of the distillation tower (303) via a furnace (302) where it is pre-heated to a temperature of about 300 °C as shown in Fig.3. The TPO is further heated in the distillation kettle to the final temperature of 380-400 °C. The "Distillation Tower" is subsequently maintained at this temperature and at a slight vacuum (- 0,3 Bar.g) drawn by a separate vacuum pump system, during the steady state continuous operation. At this temperature the long-chain hydrocarbons will be cracked down to smaller chain i.e. lighter fraction oil (diesel).

The hot oil gas from the top of the "Distillation Tower" is first driven into the top condenser (304) which is operated at around 150 °C. The condensed light TPO fraction is cooled by passing through a water-cooled heat exchanger (305) and collected in a buffer storage tank (308) whereas a stream containing vapour is returned as reflux to the top of the tower. The middle fraction is drawn from the distillation tower via a water cooled heat exchanger (306) and collected in a buffer tank (309). Likewise the heavy fraction of TPO is drawn from the bottom of the tower via its cooler (307) and collected in the buffer tank (310).

The distilled TPO will have a yellowish colour as opposed to black raw TPO and it will still have a light odour (much weaker than raw TPO). It will have the properties close to those of typical diesel used for internal combustion engines (ICE) but it will probably contain some minute solid particles e.g. carbon etc which might have been entrained in the oil gas and possibly some residual water.

In the preferred application described herein there will be a specially designed deodorizing system utilizing activated carbon to remove the smell prior to passing through a centrifuge and a downstream pressure filtration unit in order to remove any residual water as well as any solid particles.

The refined TPO is stored in bulk storage tanks and periodically transferred to smaller day tanks from which it is then fed to the power generators to produce electricity. The light fraction is stored in separate buffer tank for recycling to the oil burners of the waste incinerator for heating up the distillation furnace and/or the pyrolysis reactors. Similarly, the heavy fraction is also used in the same burners after diluting with the light fraction.

The power generation process utilises standard ICE's (Internal Combustion Engines) for the production of electrical energy using the refined TPO as fuel. In the specific application described herein, two generator machines of capacity 8,0 MW each are used. All necessary auxiliary systems are included in the power plant, such as:

- Cooling Water Systems
- Lube oil systems
- Compressed air system

The invention comprises a FG (Flue Gas) treatment section to ensure a thorough and adequate emission control system which, in this specific application, is based on the requirements of the applicable EU Directives (2010/75/eu on industrial emissions, 2015/2193/eu on the limitation of emissions of certain pollutants, 2008/98/eu on incineration of wastes as well as the applicable National Laws.

It may be adapted to meet the requirements of the most stringest emission control limits applicable anywhere.

The system is also suitable to control the emissions of certain toxic pollutants such as dioxins and furans (PCDD/F's) etc. by the use of special gas incinerators with energy recovery systems whereby the temperature of the FG streams is raised to at least 850^{0}C for a minimum residence time of 2 sec.

In this specific application of the invention the FG treatment system comprises 3 lines one for each of the two power generator machines and one to handle all FG emissions from the pyrolysis and distillation plants. Each line comprises 3 systems in series, as shown in Fig.1, namely,

i) Mixing manifold and dosing systems for injecting the required chemical additives
ii) Desulphurisation system (DSOx) comprising a "candle" filter for removal of the sulphur oxides down to less than the allowable limits
iii) Denitrogenation system (DNOx) comprising again a mixing manifold and a Selective Catalytic Reactor (SCR) unit for removal of the nitrogen oxides down to less than the allowable limits

In the first line, which includes the FG stream from the waste incinerator, activated carbon is firstly injected along with Calcium Hydroxide in the mixing manifold (113). The activated carbon is used to adsorb any dioxins and furans which might be present in the FG stream from the incinerator. The Calcium Hydroxide dry sorbent is used to transform the Oxides of Sulphur (SOx) into Calcium Sulphate (gypsum powder). The FG stream containing the loaded activated carbon, the gypsum powder and any unreacted calcium hydroxide is then passed through a “candle” filter (114) where the powders are separated out and collected at the bottom of the filter unit. It is then directed to the DNOx comprising another mixing manifold (115) and an SCR (Selective Catalytic Reactor) unit (116) where urea solution is injected for transforming the oxides of Nitrogen (NOx) by chemical reaction into Nitrogen gas.

In each of the other 2 lines downstream the power generator machines, the FG stream through the DSOx and DNOx systems in series as in line 1 utilising the same dosing systems and chemical additives with the exception of activated carbon.

From the DNOx system the treated FG is directed to the chimney for discharge to the atmosphere with any pollutants being well within the allowable limits. A continuous emissions monitoring system may be installed on the chimney to monitor and record the pollution parameters.

All processes comprising the invention are susceptible to full automation and control by systems such as PLC (Program Logic Control) or a DCS (Digital Control System) housed in the CCR (Central Control Room).

BRIEF DESCRIPTION OF THE DRAWINGS

Fig.-1 illustrates, in the form of a simplified process flow diagram, the overall process concept and shows all processes comprising the overall concept of converting waste tyres into electricity and the co-products carbon-black (CB) and scrap steel.

Fig.-2 illustrates, in the form of a Process Flow Diagram, an exemplary system of separating the scrap steel wires from the CB and further refining and upgrading the CB

Fig.-3 illustrates in the form of a Process Flow Diagram, the process of refining and upgrading the quality of TPO (Tyre Pyrolysis Oil) comprising distillation and solids-liquid separation systems

Fig.-4 illustrates in the form of a Process Flow Diagram, an exemplary system for the size reduction, granulation and purification of the input waste tyre feed prior to pyrolysis

CLAIMS

1. A system of apparatus for converting waste vehicle tyres to electricity on a commercial scale, by the batch pyrolysis of tyres producing liquid Tyre Pyrolysis Oil (TPO), commercial grade Carbon Black (CB) and commercial grade scrap steel wires and utilising the TPO as fuel in power generators of the Internal Combustion Engine (ICE) type without the production of any waste products while the gaseous emissions are within allowable limits. More precisely the whole process includes the steps of:

    a) Feeding the pyrolysis reactor chamber at a steady rate with waste vehicle tyres cut into pieces typically up to 5 cm x 5 cm using a combination of bucket elevators, chain conveyors and screw conveyors, arranged in series, into the pyrolysis chamber.
    b) Pyrolysis of the cut tyres by applying heat and maintaining the reactor chamber temperature at a predetermined level whilst maintaining a slight vacuum in the pyrolysis chamber
    c) Continuously drawing off the hydrocarbon (HC) gases via a separation vessel separating out and collecting in a tank any entrained solid and/or liquid wastes which are transported and burned in a downstream waste incinerator.
    d) Continuously cooling and condensing the condensable fraction of the HC gas into liquid Tyre Pyrolysis Oil (TPO) which is collected in an intermediate storage tank and at the same time drawing off and collecting the non-condensable fraction of the HC gas, referred to as 'Syngas' into a bulk storage tank
    e) Continuously discharging the solid residue, a mixture of Carbon Black (CB) and steel wire pieces and transferring it to a downstream separation and upgrading system
    f) Separating the CB and steel wire components of the mixture and further treating them to produce commercial grade Pyrolysis Carbon Black (PCB) and saleable scrap steel
    g) Further processing the TPO through a distillation column unit producing at least three fractions namely Light, Heavy and Middle fraction TPO and storing them in intermediate bulk storage tanks
    h) Producing electricity by one or more power generator units of the Internal Combustion Engine (ICE) type using the Middle fraction TPO as the fuel
    i) Producing additional electricity in a separate Gas Turbine Generator system which utilises the non-condensable HC Gas (termed Syngas) as fuel
    j) Treating the flue gases from the power plant and all other units to remove pollutants in accordance to environmental regulations prior to discharge to the atmosphere via a stack.

2. An apparatus according to claim 1 further characterised in including one or more pyrolysis steel chambers of the horizontal, rotary type driven by a gear-motor assembly and having an external jacket for indirect heat transfer and having a bottom combustion chamber fitted with at least two liquid fuel burners and at least two gas

burners. The pyrolysis chamber is further characterised in that it is operated at a slight vacuum by connection to a gas extraction system and at a predetermined temperature profile with the final pyrolysis stage temperature not exceeding 420 °C ensuring that any dioxins will not go into the HC gas stream.

3. An apparatus according to claim 1 further characterised in including a system of multiple condensers of the vertical shell-and-tube type, arranged in parallel and/or series or any combination thereof, whereby the condensable fraction of the HC gas coming from the pyrolysis chamber is condensed into liquid TPO and collected in a bottom tank as a mixed liquid product or separate fractions of liquid products of differing compositions thus segregating the fraction containing furans which are toxic pollutants enabling the power generation system to have emissions within allowable limits.

4. An apparatus according to claim 1 further characterised in including a system for drawing off and collecting the non-condensable fraction of the HC gas stream, referred to as 'Syngas' into a bulk storage tank and recirculating for combustion in the gas burners of the pyrolysis chambers referred to in claim 2 and/or any other gas burners in the same plant.

5. An apparatus according to claim 1 further characterised in including a distillation column and ancillary equipment for separating the TPO into three fractions namely,
   a) Light fraction TPO
   b) Middle fraction TPO
   c) Heavy fraction TPO

   The Middle fraction shall have basic properties similar to diesel which make it suitable for effective use as a fuel in ICE's for producing electricity whereas the Light and Heavy fractions can be used separately and/or mixed together as fuel in the liquid fuel burners of the pyrolysis reactors, the waste incinerator and/or any other plant units requiring heat energy.

6. A system according to claim 1 further characterised in including one or more power generating sets of the ICE type for effectively and efficiently producing electricity on a commercial scale using the Middle fraction TPO, referred to in claim 5, as the fuel, maximising the energy output.

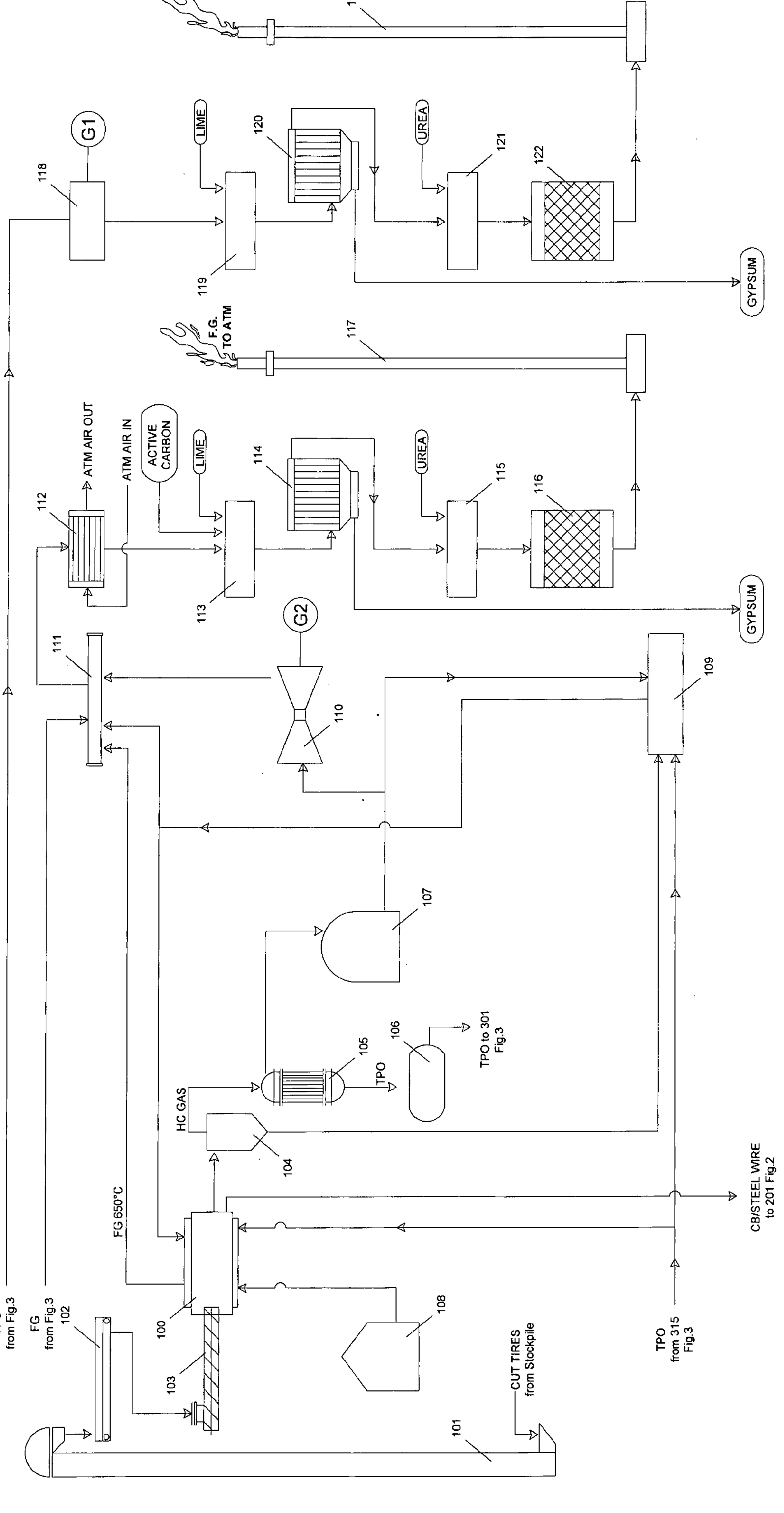
7. An apparatus according to claim 1 further characterised in including a system for separating and further processing the pyrolysis solid by-products producing commercial grade CB and saleable scrap steel wires pressed into bales.

8. An apparatus according to claim 1 further characterised in including a waste incinerator fitted with apparatus for feeding solid and/or liquid wastes and fitted with at least two liquid fuel and at least two gas burners, whereby all wastes referred to in claim 1 (c) are burned without having to be disposed outside the plant boundaries.

9. An apparatus according to claim 1 further characterised in including a system for treating the flue gas (FG) to comply with environmental regulations and comprising one or more set of gas incinerator and heat recovery gas-gas heat exchanger upstream the incinerator and downstream denitrogenation (DNOx) and desulphurisation (DSOx) units prior to discharge to the atmosphere via one or more chimneys.

10. The DNOx unit according claim 9 is further characterised as a complete system comprising an in-line Selective Catalytic Reactor (SCR) whereby urea solution is injected to convert the oxides of Nitrogen (NOx) into elemental nitrogen.

11. The DSOx unit according to claim 9 is further characterised as a complete system comprising a candle filter system with an upstream mixing duct where dry sorbent e.g. Calcium Hydroxide in fine powder form is injected to transform the oxides of Sulphur (SOx) into Calcium Sulphate (gypsum) which is used as such as an input material or in brick-making in the construction sector. In the same mixing duct dry activated carbon may also be injected for removing any toxic pollutants such as dioxins and furans. sludge and a filter press system operating at high pressure whereby the gypsum is filtered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LIME
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UREA
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GYPSUM
F.G. TO ATM
117
ATM AIR OUT
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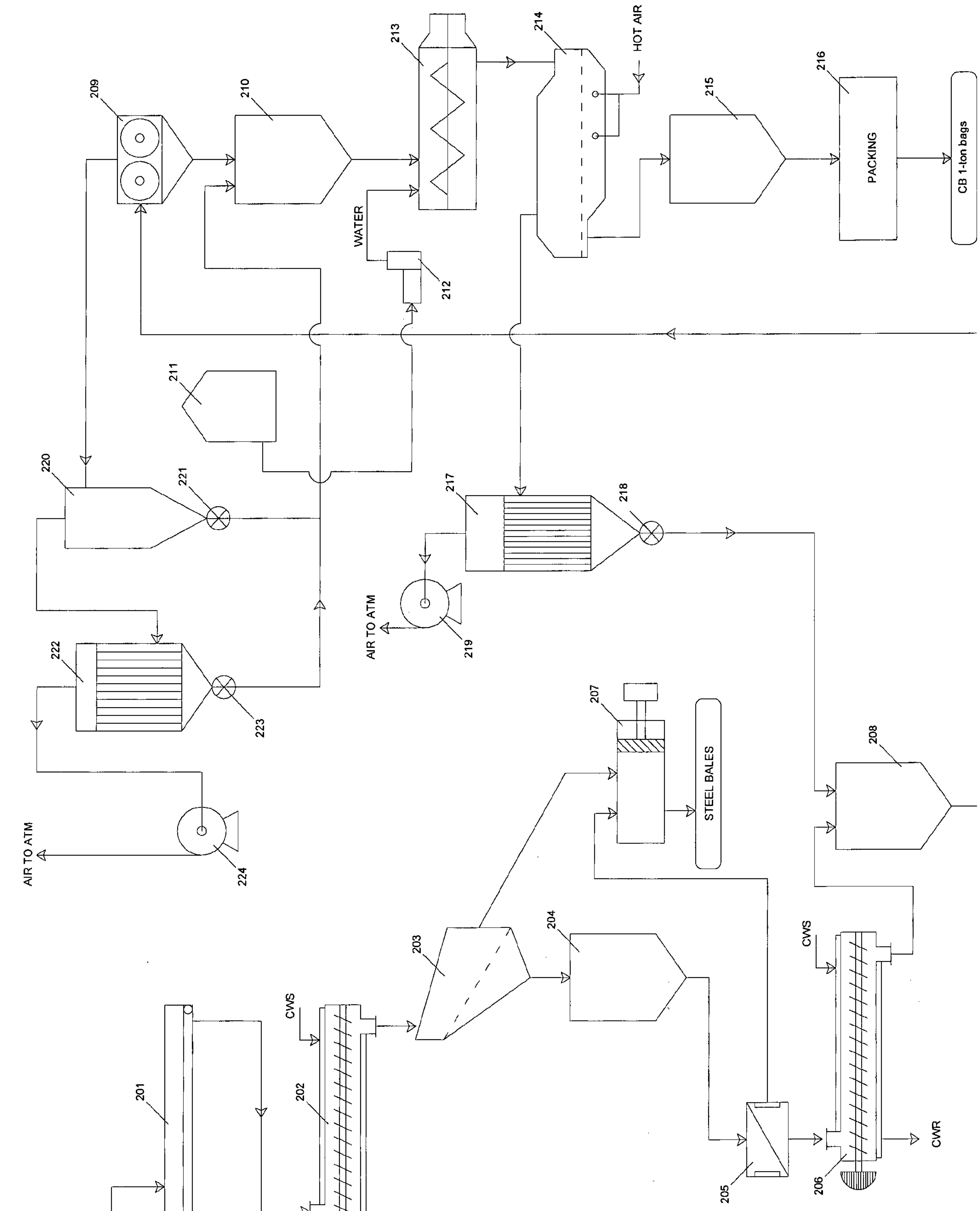
ACTIVE CARBON
LIME
112
114
UREA
115
116
113
GYPSUM
G2
111
110
109
107
106
TPO to 301 Fig.3
105
TPO
HC GAS
104
FG 650°C
CB/STEEL WIRE to 201 Fig.2
TPO from Fig.3
FG from Fig.3
102
100
108
103
CUT TIRES from Stockpile
101
TPO from 315 Fig.3

Fig. 1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210
213
214
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215
216
PACKING
CB 1-ton bags
WATER
212
211
220
221
217
218
AIR TO ATM
219
222
223
224
AIR TO ATM
207
STEEL BALES
208
203
204
CWS
CWS
201
202
CB/STEEL WIRE
from 103
Fig.1
CWR
205
206
CWR

Fig.2

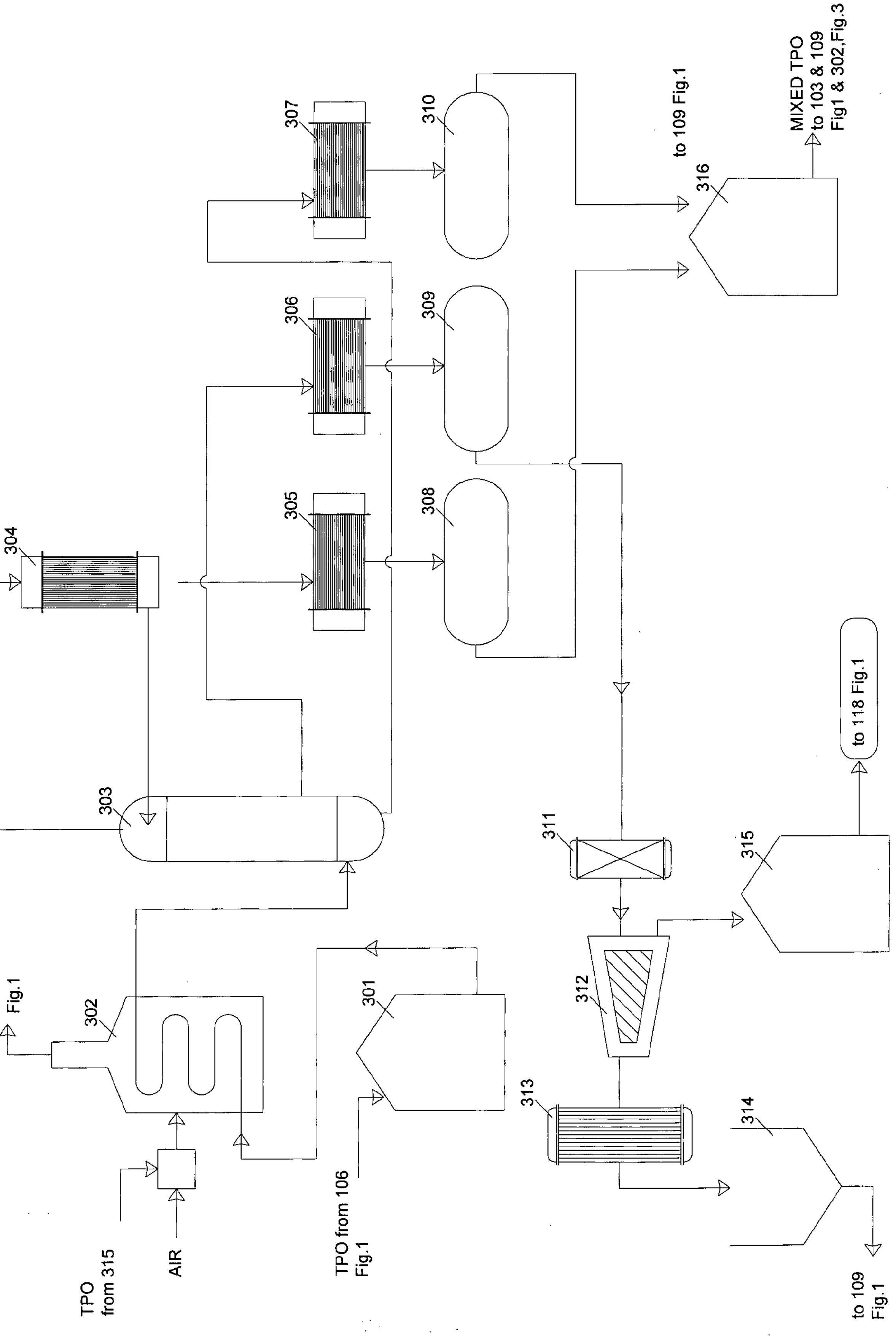
FG to 111
Fig.1
302
TPO
from 315
AIR
301
TPO from 106
Fig.1
303
304
305
306
307
308
309
310
to 109 Fig.1
316
MIXED TPO
to 103 & 109
Fig1 & 302,Fig.3
311
312
313
314
315
to 118 Fig.1
to 109
Fig.1

Fig.3

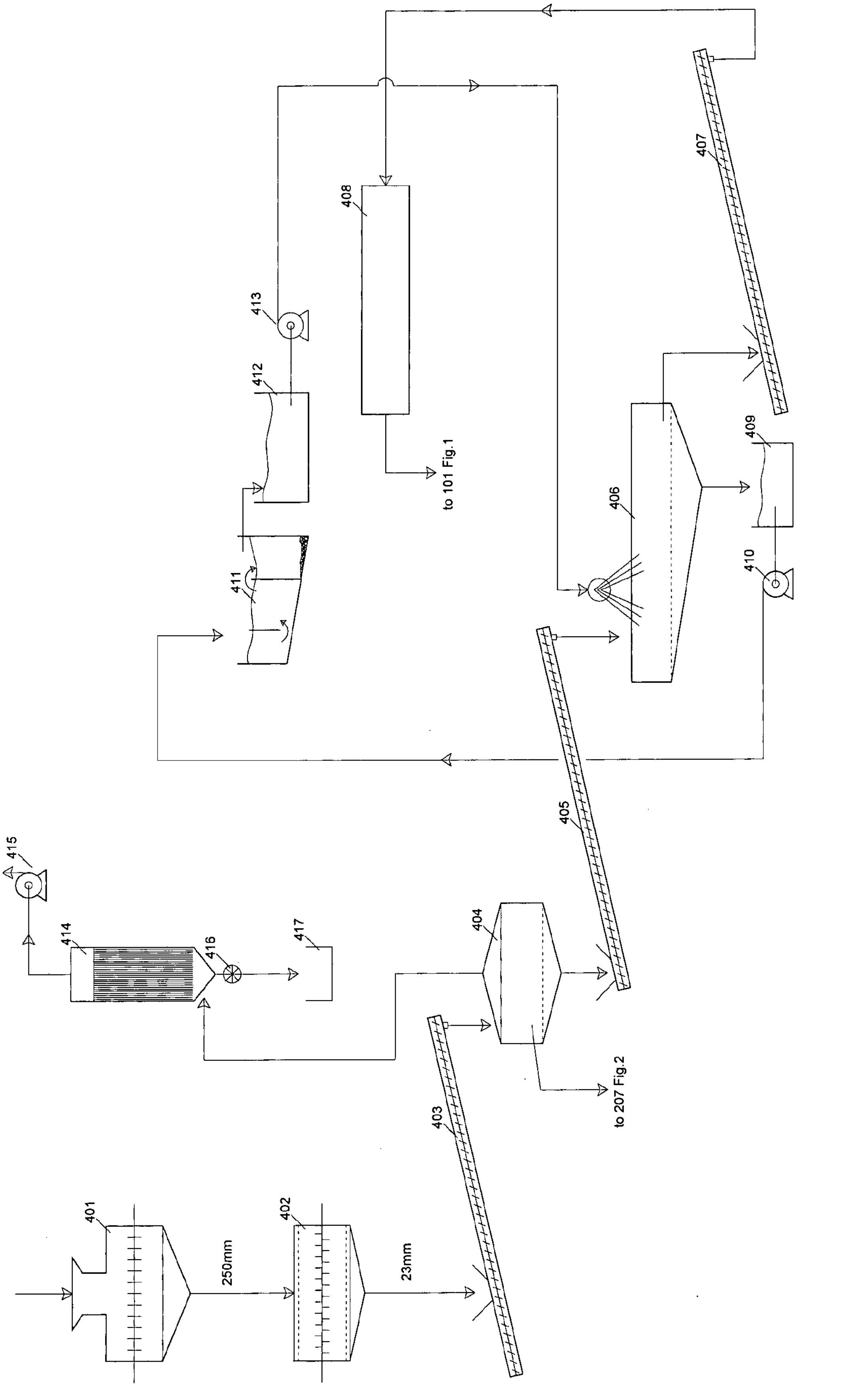
401
250mm
402
23mm
403
404
to 207 Fig.2
414
415
416
417
405
406
407
408
to 101 Fig.1
409
410
411
412
413

Fig.4