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(54) **Title**: A METHOD OF REGENERATING AN ABSORBENT FOR CAPTURE OF CARBON DIOXIDE

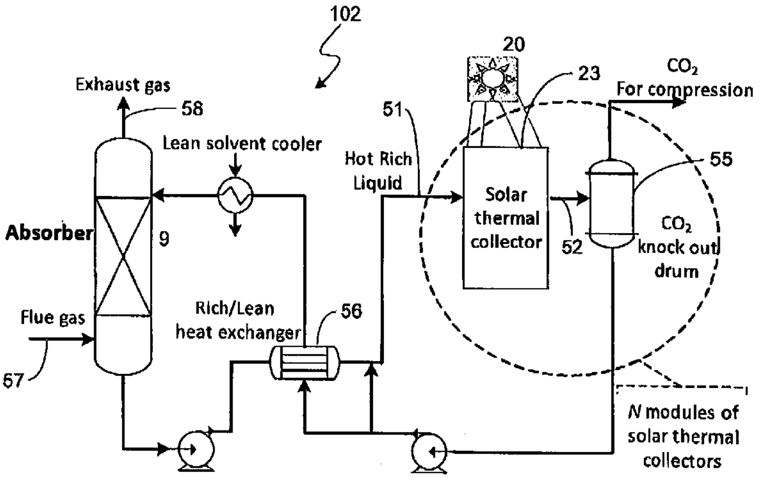

Figure 12

(57) **Abstract**: A method of regenerating a carbon dioxide rich liquid solvent wherein the method includes heating the carbon dioxide rich liquid solvent in a vessel to separate carbon dioxide gas from the liquid solvent wherein heating the carbon dioxide rich liquid solvent is provided by heating the vessel via radiative heat transfer of solar energy.

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A method of regenerating an absorbent for capture of carbon dioxide

The present invention relates to a method of regenerating a solvent used in the absorption of carbon dioxide from a flue gas, and in particular to a method of regenerating a solvent using solar energy.

Background

Carbon-based fossil fuel resources comprise today about 86% of global primary energy and they are said to be a major contributor to global warming. Power plant, transportation, and industry converted this fuel into approximately 29 billion metric tonnes CO_2 in 2006 while this is expected to grow to 33.1 and 40.4 billion metric tonnes CO_2 by 2015 and 2030, respectively (EIA, 2009). The recent Copenhagen meeting on climate change highlighted a frantic need to reduce global emissions so as to hold the increase in global temperature below 2 degrees Celsius (equivalent to 450 parts per million of CO_2) (UNFCCC, 2009). World Energy Outlook 2009 (IEA, 2009) estimated that capping atmospheric temperature rise below 2°C by 2030 requires avoiding of CO_2 at 3.8 and 13.8 billion metric tonnes by 2020 and 2030, respectively. This represents a significant escalation in CO_2 abatement. Such a goal requires an additional US$10.5 trillion of cumulative energy-related investment.

The main options for reducing carbon emissions are: (1) reduction of energy usage, e.g. via efficiency improvement, (2) replacing fossil fuels by zero or reduced carbon-emitting sources, such as renewable, biofuels and nuclear, and (3) capture and storage of CO_2. Although the best alternative route to solving the carbon emissions problem would be to use renewable energy sources, these energy sources are not currently competitive with fossil fuels in terms of cost and feasibility. As such, fossil fuels will continue to be relied on in the next few decades. Carbon capture and storage (CCS) is therefore viewed as a medium-term solution and a bridge from the current fossil fuel-based energy system to one that has near-zero carbon emissions. Therefore, by developing technologies for CCS, we can reduce emissions in the medium-term as we move to large scale use of renewable, carbon-free energy sources.

Power plants account for about 78% of worldwide large stationary CO_2 sources where the other large CO_2 emitting industries are cement (7%), refineries (6%), and iron and steel (5%). Hence, power plants are the main focus in implementation of CCS projects. Among the power plants, however, the pulverized coal-fired type is of great concern due to its high attribution to Carbon Intensity (CI). The CI of coal, oil and natural gas are 24.5, 20.3 and 13.8 kg-C/MJ, respectively (EPRI, 2009). This means that coal power plants, on average, emit 1.78 times the emission of those with natural gas. This value becomes much higher if the lower efficiency of coal-fired power plants compared with natural gas combined cycle (NGCC) is considered.

Soon after the emergence of the UNFCCC (United Nations Framework Convention on Climate Change) treaty on GHG emission reduction, research on different alternative approaches for separation of CO_2 from flue gas accelerated due to the high forecast commercial value. Since then, a few technologies have been described for PCC, namely solvent-based absorption-desorption, membrane, adsorption and mineralization (See Figure 1).

Among these, solvent and membrane technologies seem to be the most reliable in the medium term. Post-combustion carbon capture from flue gas (using solvent technology) is well understood and is currently used in different industrial applications. In fact, PCC started in the 1970s, not with the concern for its global warming effect, but as a potential economic source of CO_2, mainly for enhanced oil recovery (EOR) operations. For this reason solvent-based PCC is almost ready today while other PCC technologies (membrane, adsorption, etc.), pre-combustion and oxyfuel methods are still in development phase. As such, solvent-based PCC may be the most accessible option for retrofitting existing power plants.

Figure 2 shows a schematic of a solvent-based PCC process. The flue gas passes through the absorber column (packed or tray) where the lean solvent enters from the top of the absorber in a countercurrent process. In the absorber, the solvent removes CO_2 from the flue gas through exothermic physico-chemical interaction; the rich solvent then exits from the absorber bottom, with higher temperature, while the cleaned flue gas leaves absorber overheads towards stack. In the stripper column, the rich solvent is stripped of CO_2 via thermal treatment. The lean solvent is recycled to absorber while CO_2 is sent from overhead to a compression unit.

Despite notable developments in solvent-based absorption-desorption processes, over five decades, the implementation of this technology incurs a notable energy penalty, mainly due to solvent regeneration. The energy for solvent regeneration of the PCC process is typically supplied by bleeding steam from power plant steam cycle. Furthermore, the PCC needs electricity for its auxiliary equipments including liquid pumps and CO_2 compressors. The overall energy penalty is estimated to be above 20%. This results in serious reduction in power plant efficiency.

The present invention seeks to provide a method of solvent regeneration which is more energy efficient and which thereby provides a post-combustion carbon capture process with a significantly reduced energy penalty than current processes.

Summary

According to one aspect there is provided a method of removing at least part of the carbon dioxide from a flue gas, the method including the following steps:

a. contacting the flue gas with a liquid solvent in an absorber wherein at least part of the carbon dioxide contained in the flue gas is absorbed by the solvent thereby providing a first exit stream from the absorber including carbon dioxide rich liquid solvent and a second exit stream from the absorber including flue gas with a reduced carbon dioxide concentration; and,

b. heating the carbon dioxide rich liquid solvent in a vessel to separate carbon dioxide gas from the liquid solvent thereby providing a regenerated liquid solvent and a gas stream of carbon dioxide, wherein heating the carbon dioxide rich liquid solvent in step b is provided by heating the vessel via radiative heat transfer of solar energy.

According to another aspect there is provided a method of regenerating a carbon dioxide rich liquid solvent wherein the method includes heating the carbon dioxide rich liquid solvent in a vessel to separate carbon dioxide gas from the liquid solvent wherein heating the carbon dioxide rich liquid solvent is provided by heating the vessel via radiative heat transfer of solar energy.

In one form the carbon dioxide rich liquid solvent is heated in step b. by the body of the vessel which in turn is heated via radiative heat transfer of solar energy. In one form the radiative heat transfer of solar energy is provided by an array of solar energy collectors.

According to another aspect there is provided a method of removing at least part of the carbon dioxide from a flue gas, the method including the following steps:

a. contacting the flue gas with a liquid solvent in an absorber wherein at least part of the carbon dioxide contained in the flue gas is absorbed by the solvent thereby providing a first exit stream from the absorber including carbon dioxide rich liquid solvent and a second exit stream from the absorber including flue gas with a reduced carbon dioxide concentration; and,

b. heating the carbon dioxide rich liquid solvent in a vessel to separate carbon dioxide gas from the liquid solvent thereby providing a regenerated liquid solvent and a gas stream of carbon dioxide,

wherein heating the carbon dioxide rich liquid solvent in step b is provided by contacting the carbon dioxide rich liquid solvent with a condensing end of a heat pipe wherein heat is transferred to the heat pipe via radiative heat transfer of solar energy.

According to another aspect there is provided a method of regenerating a carbon dioxide rich liquid solvent wherein the method includes heating the carbon dioxide rich liquid solvent in a vessel to separate carbon dioxide gas from the liquid solvent wherein wherein heating the carbon dioxide rich liquid solvent in step b is provided by contacting the carbon dioxide rich liquid solvent with a condensing end of a heat pipe wherein heat is transferred to the heat pipe via radiative heat transfer of solar energy.

In one form the vessel is in the form of a pipe or conduit.

In one form wherein the condensing end of the heat pipe protrudes into the body of the vessel.

In one form the regenerated liquid solvent passes through a knock out drum where gaseous carbon dioxide is removed from the regenerated solvent.

Brief Description of the Accompanying Figures

The present invention will become better understood from the following detailed description of various non-limiting embodiments thereof, described in connection with the accompanying figures, wherein:

Figure 1 is a Schematic of CO_2 emitting process with Post Carbon Capture (PCC) facility;

Figure 2 is a Schematic of a solvent-based PCC Process;

Figure 3 is a Schematic of desorber with a kettle reboiler;

Figure 4 is a Schematic of a coal-fired power plant with retrofitted PCC;

Figure 5 is a Schematic of some options for fossil fuel-based repowering of power plants integrated with solvent-based PCC processes; a) base-case scenario, b) repowering with boiler, and c) repowering with natural gas turbine;

Figure 6 is a Schematic of some options for renewable energy based repowering of power plants integrated with solvent-based PCC processes; repowering with a) solar energy, and b) wind energy;

Figure 7 is a Schematic of a coal-fired power plant with PCC while sourcing the reboiler energy from steam cycle and solar thermal energy;

Figure 8 is switching scheme for flexible operation of power plant;

Figure 9 is a Schematic of an evacuated tube collector (heat pipe) as an example of a solar collector;

Figure 10 is a structure of the heat transfer based on the available methodologies.

Figure 11 is a schematic of the heat transfer arrangement to the carbon dioxide rich solvent to produce the regenerated solvent in accordance with an embodiment,

Figure 12 is a Schematic process diagram of a PCC process where the carbon dioxide rich solvent is regenerated by direct solar energy in accordance with one embodiment;

Figure 13 is a Schematic of a coal-fired power plant with retrofitted PCC process in accordance with embodiment of Figure 12;

Figure 14 is a Schematic of a solar-assisted PCC in accordance with one embodiment with storage during a) day (sun available), b) night (sun unavailable). Grey color indicates the process inactivity.

Figure 15 is a Relation between solar fraction and a) solar collector area; b) annual economic benefit

Figure 16 is the relationship between solar collector area and carbon capture capacity; and,

Figure 17 is the Economic comparison of conventional methodology and the current invention.

Detailed Description

The foregoing describes only some embodiments of the present invention, and modifications and/or changes can be made thereto without departing from the scope and spirit of the invention, the embodiments being illustrative and not restrictive.

In the context of this specification, the word “comprising” means “including principally but not necessarily solely” or “having” or “including”, and not “consisting only of”. Variations of the word "comprising", such as “comprise” and “comprises” have correspondingly varied meanings.

Referring to figures 2 and 3 there is shown a typical solvent-based Post Carbon Capture (PCC) process 100 wherein the objective of the desorber 10 (also referred to in the art as a stripper) is to heat the liquid solvent rich in carbon dioxide in order to force the reverse kinetics to release the carbon dioxide. In cases when the saturation temperature of solvent and solute are very different then part of the solvent mixture can be evaporated to provide the stripping fluid. For instance, MEA has a saturation temperature of 170.4°C at atmospheric pressure, which is quite remote from that of water, being 100°C. Therefore, part of the liquid reaching the bottom of the desorber column 10 can be heated (reboiled) to a certain temperature to generate steam (see Figure 3). Further to this the recycled liquid from the condenser 5 can also be used for steam generation (see Figure 2). Therefore the key issues in desorber 10 design are reboiler pressure, reboiler temperature, and gas (steam) flowrate in the desorber column 10.

Reboiler 6 pressure and temperature are among the most critical (if not the main) parameters in desorber 10 design. The reboiler 6 pressure should be enough to compensate for the pressure drop of the packed column and allow the gas phase (steam) to move up. That is the minimum requirement for reboiler 6 pressure. However, high pressures are usually preferred for the desorber 10 because of the intensity of the process and the ability to work at higher temperatures without fear of more liquid vaporization. However, the pressure has an upper limit, enforced by (1) the economics of the system, either capital expenditures (CAPEX) or operational expenditures (OPEX), and (2) the solvent degradation temperature.

The reboiler 6 temperature is more complex than the pressure. Theoretically, a higher desorber 10 (reboiler) temperature will expedite the regeneration process. However, there is an upper bound for this temperature, enforced by process techno-economics and by two main issues: (1) a higher reboiler 6 temperature means higher quality of utility steam, which increases the operating costs of the process; (2) high temperatures result in solvent degradation. Therefore, for any solvent there is a degradation temperature (T^{Deg}) that the reboiler 6 temperature should not exceed. As such, the reboiler 6 temperature constraint can be written as

$$T_{Reb} < \min(T^{sat}(P), T^{Deg}) \quad (1)$$

where $T^{sat}(P)$ is obtained from flash vapor-liquid equilibrium calculations at pressure P. A simple $T^{sat}(P)$ can be obtained from Raoult's law, given by

$$T^{sat}(P) = x_{solv.}T^{sat}_{solv.}(P) + (1 - x_{solv.})T^{sat}_{H_2O}(P) \quad (2)$$

in which x_{MEA} is the molar fraction of MEA in solution. $T^{sat}_{solv.}(P)$ and $T^{sat}_{H_2O}(P)$ are the saturation temperatures of pure solvent and water at pressure P, respectively, which are usually presented by an Antoine equation.

The flowrate of the gas stream is another issue. Certainly, the objective is to use just enough steam to achieve the regeneration objective, as any extra steam will just add to the operating costs. The exit gas from the top of the desorber 10 will contain mainly the target gas (CO_2) and steam. The partial pressure of the target gas (TG) should be less than the equilibrium partial pressure of the inlet liquid $\left[(p_{CO_2})_{s=S} \leq p_{CO_2} @ \alpha = \alpha^{Des}_{int}\right]$. Otherwise, reverse mass flow will occur, meaning that instead of desorbing the carbon dioxide from the liquid, more will be absorbed. As such, the flow rate of steam at the bottom of the reboiler should be such that at the top of column the partial pressure of steam becomes greater than "$P - p_{CO_2}(\alpha^{Des}_{int})$". Moreover, the temperature of the gas at the top of the column should be higher than the inlet liquid temperature $(T^{L}_{int} < T^{G}_{out})$, to allow regeneration to initiate from the column top. It is therefore necessary that before desorber 10 modeling the reboiler temperature is decided and fed into the program. The liquid temperature at the bottom of the column can also be set a few degrees below the reboiler 6 temperature $(T^{L}_{out} = T_{Reb} - \Delta T)$.

Figure 4 illustrates the schematics of a power plant 150 retrofitted with a PCC unit 100. As shown, the flue gas passes through the absorber column 9, interacts with MEA solvent and loses its carbon dioxide content before going to stack. The steam required for the reboiler 6, can be extracted from IP or LP turbines. Therefore, the extracted steam and flue gas streams are the significant connections between power plant 150and the PCC unit 100. This illustrates the advantages of the PCC 100 process discussed above, i.e. it results in minimum modification on existing power plants.

As an example embodiment, Table 1 lists the results for integration of the base case 300 MWe coal-fired power plant with a PCC process. The integration shows that achieving 90% CO_2 capture with purity of 99% using 30 wt% Monoethanolamine MEA solvent requires 41.8% of steam of the LP turbine for solvent regeneration. This is proportional to 37.9 MWe decrease in electricity production, which is the largest consumer of energy in the PCC unit. The reboiler, therefore, imposes an energy penalty of about 13.4% to the power plant net output. This dramatic energy penalty excludes the other energy consuming equipment such as CO_2 compression, and solvent pumps which account for about 17.2 MWe. Thus, the overall energy penalty associated with retrofitting the capture unit is 19.4% of the base case power plant net output which is significant reductions in energy efficiency and thus costs.

Table 1: Power plant performance associated with retrofitting the PCC unit

Parameter	Value
gross power with PCC (MWe)	262.1
amount of steam extracted for reboiler heating (%)	41.8
reboiler share of power reduction (MWe)	37.9
reboiler energy penalty (%)	13.4
power plant auxiliary (MWe)	17.1
PCC auxiliary (compressors, flue gas blower, solvent pumps, etc.) (MWe)	17.2
net power output (MWe)	227.9
gross electrical efficiency	0.28
net electrical efficiency	0.24
net efficiency reduction due to PCC (%)	**19.4**
CO_2 emitted (kg/KWh)	0.11
CO_2 avoided (tonne/h)	230.9

The steam extraction 17 for solvent regeneration in the desorber column 10 is the main contributor for power plant load reduction (Figure 5a). Numerous approaches have been proposed for integrated operation of power plant and PCC process while satisfying the maximum benefit of the market demand of electricity. One of the early attempts has been repowering which can happen in either of two ways; one way is the installation of a small boiler 18 to generate the regeneration energy without the need for steam extraction from power plant steam cycle (Figure 5b). The other way is to extract regeneration energy from power plant steam cycle, but install a small natural gas turbine 19 to generate enough electricity to prevent load reduction (Figure 5c).

An alternative approach is the application of renewable energy sources. For example, solar energy 20 may be used for supplying energy which is then used to produce steam 23 needed for solvent regeneration in the desorber 10 (Figure 6a). Another approach is to make use of wind energy 21 (Figure 6b). The problem of renewable energies like solar or wind is their intermittencies.

Solar thermal collectors 23 are devices designed to collect and convert the electromagnetic solar irradiation energy into more usable or storable energy form. They are usually categorized into two groups of non-concentrating and concentrating where for the former the collector area and absorber area are the same while they are different for the latter. The concentrating systems are costly and are usually used for generating high temperature steam from where electricity is generated. The non-concentrating collectors are less costly and are usually used for low-medium temperature fluid heating.

Solar thermal collectors have the potential for providing sufficient energy, fully or partially, and reduce/eliminate the need for steam extraction from power plant steam cycle. This could minimize/prevent the power plant load reduction. Figure 7 illustrates a coal-fired power plant integrated with solvent based PCC process 100 and a system which makes use of solar energy 20. The viability of such solar-assisted PCC (SPCC) 101 is location specific. It depends on environmental conditions (solar irradiance), cost of electricity, land availability, etc. Regions with high insolation, long summers, air-conditioning demand, and a reliance on coal-fired power plants would be the most promising candidates for the implementation of an SPCC system. This is not only because of the availability of solar resource but also because of the correlation between high electricity demand with solar irradiance.

Another arrangement is the integration of a field of Fresnel collectors that supply heat to produce steam for the regeneration of the CO_2 solvent. This arrangement may be prohibitively expensive as a very large solar field and Thermal Storage (TS) would be required for night operation. Thus it was proposed that TS of 15 Full Load Hours (FLH) be used and an on/off switching scheme be implemented. In this on/off switching scheme, if the combined thermal energy from the collectors and storage is equal to or greater than the energy required for regeneration, the solar hot water would be used for solvent regeneration. Otherwise steam would be bled from the turbine circuit and the thermal energy would be used to regenerate the solvent. Figure 8 illustrates the switching scheme.

In accordance with certain embodiments, it is proposed to remove the desorber 10 from the post-combustion carbon capture process 100 and heat the carbon dioxide rich solvent directly with heat derived from solar energy 20. By heating the rich solvent directly, the solvent may be regenerated to a lean solvent which may then be sent for use in the absorber of the post-combustion carbon capture process.

As an example embodiment, Figure 9 shows schematic of an evacuated tube collector (also referred to as a heat pipe) in which the solar energy 20 is transferred to a liquid inside the evacuated tube. The liquid heats and moves to the tube condenser head 32 composed of copper. The heat is then directly transferred to the working fluid 33 passing through the head of the tube 32 and heats it. In accordance with an embodiment of the present invention, the working fluid 33 passed through the head of the tube 32 may be the carbon dioxide rich solvent and the heat directly transferred from the solar energy reflecting onto the evacuated tube collector is used to directly regenerate the solvent passing through as the working fluid. The tube condenser head 32 protrudes into the pipe, or vessel, through which the carbon dioxide rich solvent 33 is passing which provides a better heat transfer via conductive heat transfer.

The ultimate goal of desorber 10 is to heat the rich solvent to break the CO_2-solvent reaction bonds and separate them followed by sending CO_2 to storage and lean solvent to the absorber 9. With this if we look at the overall heat transfer structure to the rich solvent, in Figure 10, it is evident that the heat transfer from sun to the solvent passes through numerous stages (A – Heating Working Fluid Stage, B – Generation of Steam, C – Heating for steam of Reboiler, and D – The steam mixes with the rich solvent and passes its latent heat to the solvent for reverse reaction and breaking bonds) and each stage is subject to energy loss, which is compounded by the equipments and CAPEX required for each heat transfer stage.

In accordance with embodiments of the present invention the rich solvent 51 may be directly sent to the solar collector 23 where the heat transferred breaks the carbon dioxide solvent bonds of the carbon dioxide rich solvent 51 and changes the solvent to a regenerated solvent, or lean solvent, 52, without sending the solvent to a desorber 10. The analogical heat transfer structure of Figure 10 in the current methodology is illustrated in Figure 11. It is clear that such an arrangement has a significant advantage in the extent of the reduction of both the capital expenditure and operating expenditure of a typical PCC process 100.

The schematic solvent-based PCC process in accordance with an aspect of the present invention is shown in Figure 12. It is evident from the figure that the desorber column 10 along with the CO_2 condenser 5 and reboiler 6 are removed from the process flow diagram altogether.

Referring to figure 12, flue gas 57 including carbon dioxide is introduced to an absorber 9 which removes at least some of the carbon dioxide from the flue gas by directly contacting and absorbing the carbon dioxide with a liquid solvent such as MEA. The flue gas which has had carbon dioxide removed can exit at the top of the absorber column 9 via exhaust gas 58 which would be normally sent to a stack. The solvent rich in carbon dioxide exits the bottom of the absorber and is sent via a heat exchanger 56 to a solar thermal collector 23 which receives solar radiation from the sun and provides heat to the carbon dioxide rich solvent 51 via radiative heat transfer which breaks the carbon dioxide solvent bonds of the carbon dioxide rich solvent 51 and changes the solvent to a regenerated solvent, or lean solvent, 52. The lean solvent 52 exits the solar thermal collector 52 which includes carbon dioxide which is then removed from the stream 52 by a knock out drum 55 which sends the regenerated solvent from the bottom stream of the knock out drum 55 back to the absorber via heat exchanger 56 and releases the separated carbon dioxide from the top of the knock out drum 55. The carbon dioxide may then be sent for compression, storage, further industrial use or sequestration as desired.

The integration of the power plant 150 and the proposed process in accordance with one embodiment is illustrated in Figure 13 and 14. In the integrated structure, two optional storage tanks 60, 61(for lean 61 and rich solvent 60) are allocated for the conditions when the CO_2 capture process 102 continues during the times when solar energy is unavailable. Under this scenario the solar collection field 23 will be sized in such a capacity that it can provide enough energy for continuous solvent regeneration. During sun unavailability, rich solvent from absorber 58 will be directed to rich solvent tank 60 and stored (Figure 14b). When solar radiation is available (during day) the solar field will regenerate both the stored rich solvent 67 and the rich solvent 57 coming directly from absorber (Figure 14a). The same amount of stored rich solvent 67 after regeneration will be stored in lean tank 61 for use during sun unavailability.

The key advantages of the arrangement in accordance with various embodiments of the invention are:

- Unlike the conventional PCC 100 (Figure 2) or solar-assisted PCC 100 (Figure 7), the present invention decouples the PCC system from power plants with eliminating the dependence of the PCC process on the power plant steam cycle. This reduces the operation complexity of power plant with carbon capture process. In the conventional method, however, the steam for the reboiler has to be bled from power plant steam cycle. This requires modification in the steam cycle and operation of the integrated process becomes complex.
- The present invention does not require desorber column, CO_2 condenser, and reboiler which is subject to notable reduction in capital costs in the range of 25-30%.
- As illustrated in Figure 10, in conventional arrangements a notable amount of solar energy is lost because of using numerous heat transfer mediums while in the

current methodology solar energy is directly transferred to the rich solvent. In other words, the size of solar panel in this embodiment will notably decrease translating to further saving in capital and operation costs.

- The partial pressure of the CO_2 in the desorber column should be less than the equilibrium partial pressure of the inlet rich solvent. Otherwise, reverse mass transfer will occur, meaning that instead of desorbing the target component from the solvent, more CO_2 will be absorbed. As such, the flow rate of steam at the bottom of the reboiler should be high enough that at the top of column the partial pressure of steam becomes greater. This means that the energy of steam which is generated in the desorber column is much more than the energy required for solvent regeneration. For instance, while the theoretical regeneration energy for MEA is around 2-2.5 MJ/kg-CO_2 (depending on operating temperature), the reboiler energy is reported at best conditions around 3 MJ/kg-CO_2 and generally in the range of 3.5-5.0 MJ/kg-CO_2. In the present invention, the solvent receives the energy directly from sun without need to contact with steam. As such the energy duty will be quite close to its theoretical value (2.9 MJ/kg-CO_2 for the case-study discussed below).
- The product CO_2 stream will be combination of steam and CO_2 (with steam molar fraction being above 50%), notable cooling duty is required to cool the CO_2-water stream and separate CO_2. In the method of the present invention, the CO_2 condenser is removed from the process and not required.
- The operation of desorber column is very complex, compared with absorber, due to its integration with reboiler and condenser. The elimination of desorber system will add further flexibility for power plant operation with respect to market dynamics.

The invention will be further described with reference to the following non-limiting example.

Example

A 660 MWe coal-fired power plant is burning pulverized black coal and emitting 595 tonne/h of CO_2. The power plant aims to build a solvent-based PCC plant to capture 1.5 million tonnes of CO_2 annually starting from year 2015. The selected process is using 30 wt% Monoethanolamine MEA solvent with 90% CO_2 capture with product CO_2 purity of 99%. Such a plant will require 151.2 MWth energy for solvent regeneration which should be supplied by steam extraction from power plant steam cycle. This amount of thermal energy will reduce power load about 26.8 MWe. The company has investigated the application of evacuated tube solar thermal collectors for supplying part/whole of regeneration energy. Figure 15a illustrates the relation between solar collector area and its fractional share of regenerator energy. It is evident from the figure, that at higher solar fractions (i.e. above 0.8) the required solar collector area increases exponentially. For instance, while satisfying 80% of regeneration energy by solar system, requires collector area of 2×106 m2, it skyrockets to 6×106 m2 just by slight increase of solar fraction to 90%. Figure 15b shows the economic benefit of using solar collectors instead of steam extraction from power plant. It is evident from the figure, that solar system is less economical attractive at higher solar fractions.

A scenario whereby the desorber is removed from the system and solar collector acts to directly regenerate the solvent was also investigated. In this example, the entire regeneration energy must be supplied by solar system due to inexistence of desorber. Figure 16 illustrates the area required for achieving the total solvent regeneration at various carbon capture rates. To capture of 1.5 million tonne of CO_2 annually, area of $2.64\times106\ m^2$ is required. Apart from the economic differences, such an area could only supply 84% of regeneration energy using conventional methodologies (Figure 15a).

The economic comparison of the two methodologies is illustrated in Figure 17. It is evident from the figure that the proposed methodology has notable economic advantage over the conventional methodology. For instance, to capture 1.5 million tonne of CO_2 using $2.64\times106\ m^2$ collector area, the relative annual benefit for the conventional methodology is 74.1 whilst the same is 96.1 for the current proposed methodology. This translates to

29.7% higher annual benefit, being about A$11.12 million per year for the small scale example given.

Many modifications will be apparent to those skilled in the art without departing from the scope of the present invention.

The Claims:

1. A method of removing at least part of the carbon dioxide from a flue gas, the method including the following steps:
    a. contacting the flue gas with a liquid solvent in an absorber wherein at least part of the carbon dioxide contained in the flue gas is absorbed by the solvent thereby providing a first exit stream from the absorber including carbon dioxide rich liquid solvent and a second exit stream from the absorber including flue gas with a reduced carbon dioxide concentration; and,
    b. heating the carbon dioxide rich liquid solvent in a vessel to separate carbon dioxide gas from the liquid solvent thereby providing a regenerated liquid solvent and a gas stream of carbon dioxide,

wherein heating the carbon dioxide rich liquid solvent in step b is provided by heating the vessel via radiative heat transfer of solar energy.

2. A method of regenerating a carbon dioxide rich liquid solvent wherein the method includes heating the carbon dioxide rich liquid solvent in a vessel to separate carbon dioxide gas from the liquid solvent wherein heating the carbon dioxide rich liquid solvent is provided by heating the vessel via radiative heat transfer of solar energy.

3. A method according to claim 1 or claim 2 wherein the carbon dioxide rich liquid solvent is heated in step b. by the body of the vessel which in turn is heated via radiative heat transfer of solar energy.

4. A method according to any one of claims 1 to 3 wherein the radiative heat transfer of solar energy is provided by an array of solar energy collectors.

5. A method according to claim 1 or claim 2 wherein the vessel is in the form of a pipe or conduit.

6. A method of removing at least part of the carbon dioxide from a flue gas, the method including the following steps:
    a. contacting the flue gas with a liquid solvent in an absorber wherein at least part of the carbon dioxide contained in the flue gas is absorbed by the solvent thereby providing a first exit stream from the absorber including carbon dioxide rich liquid solvent and a second exit stream from the absorber including flue gas with a reduced carbon dioxide concentration; and,
    b. heating the carbon dioxide rich liquid solvent in a vessel to separate carbon dioxide gas from the liquid solvent thereby providing a regenerated liquid solvent and a gas stream of carbon dioxide,

   wherein heating the carbon dioxide rich liquid solvent in step b is provided by contacting the carbon dioxide rich liquid solvent with a condensing end of a heat pipe wherein heat is transferred to the heat pipe via radiative heat transfer of solar energy.

7. A method of regenerating a carbon dioxide rich liquid solvent wherein the method includes heating the carbon dioxide rich liquid solvent in a vessel to separate carbon dioxide gas from the liquid solvent wherein wherein heating the carbon dioxide rich liquid solvent in step b is provided by contacting the carbon dioxide rich liquid solvent with a condensing end of a heat pipe wherein heat is transferred to the heat pipe via radiative heat transfer of solar energy.

8. A method according to claim 6 or 7 wherein the vessel is in the form of a pipe or conduit.

9. A method according to any one of claims 6 to 9 wherein the condensing end of the heat pipe protrudes into the body of the vessel.

10. A method according to any one of the preceding claims wherein the regenerated liquid solvent passes through a knock out drum where gaseous carbon dioxide is removed

from the regenerated solvent.

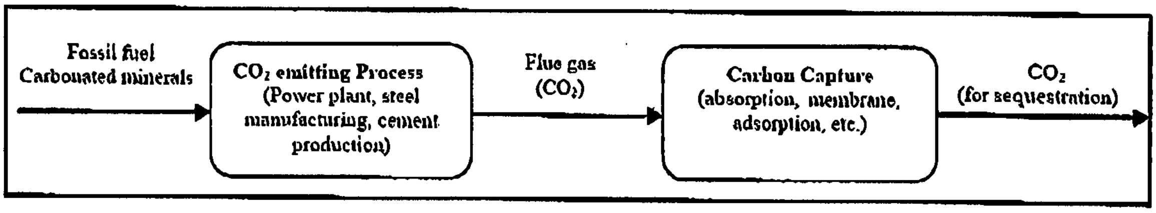

Figure 1

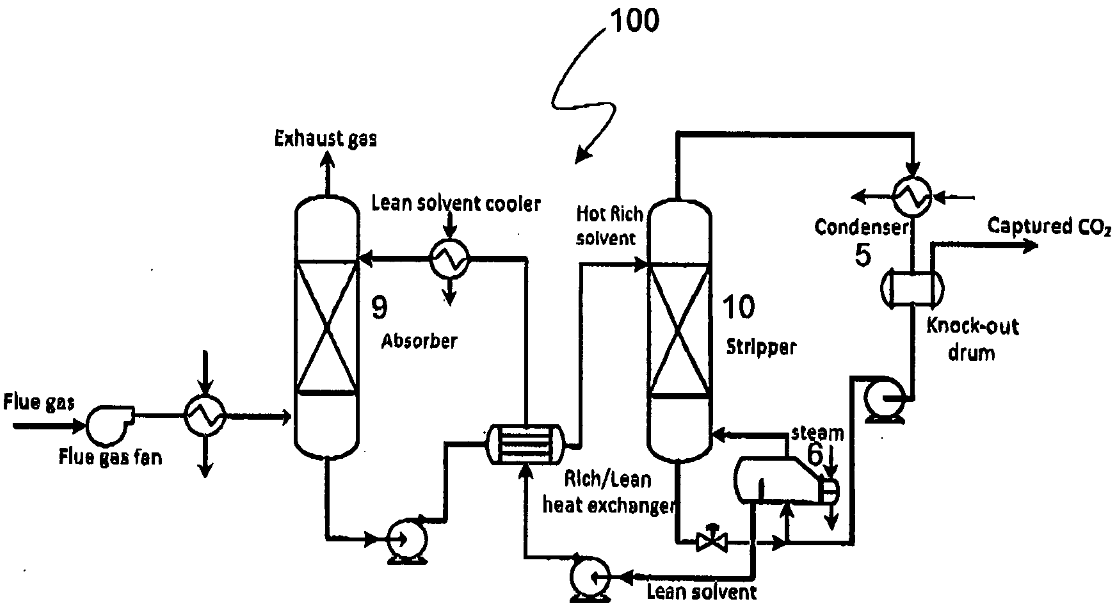

Figure 2

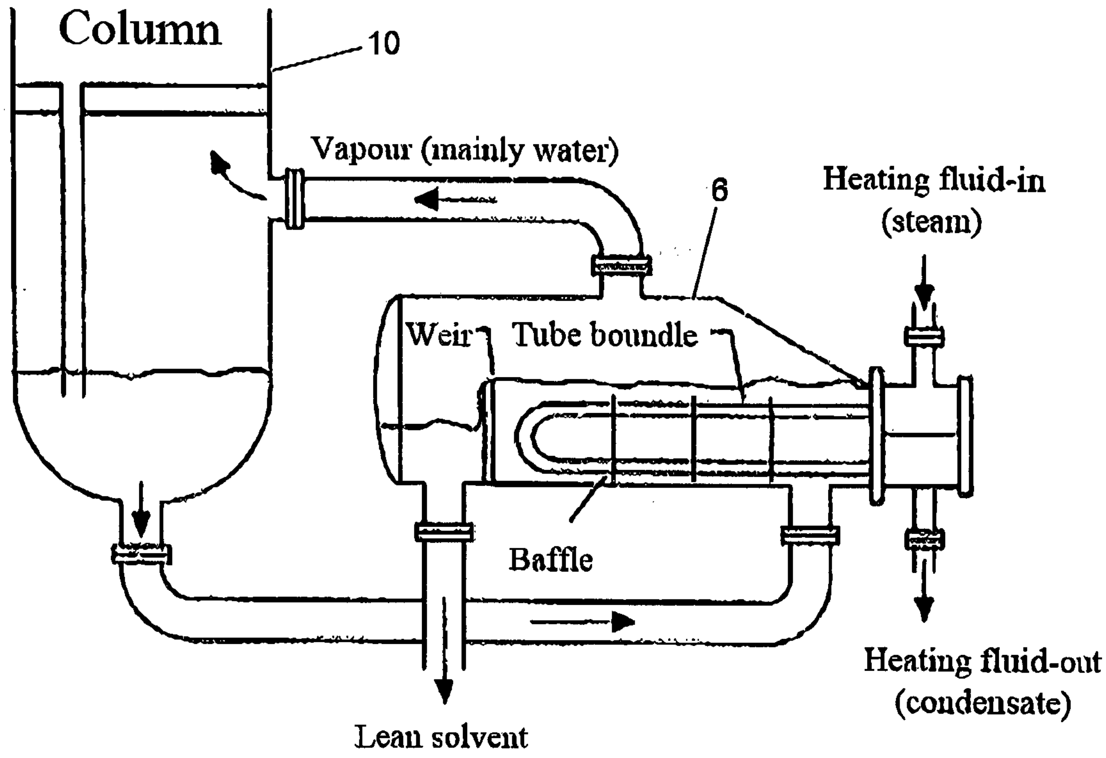
Column
10
Vapour (mainly water)
6
Heating fluid-in
(steam)
Weir
Tube boundle
Baffle
Heating fluid-out
(condensate)
Lean solvent

Figure 3

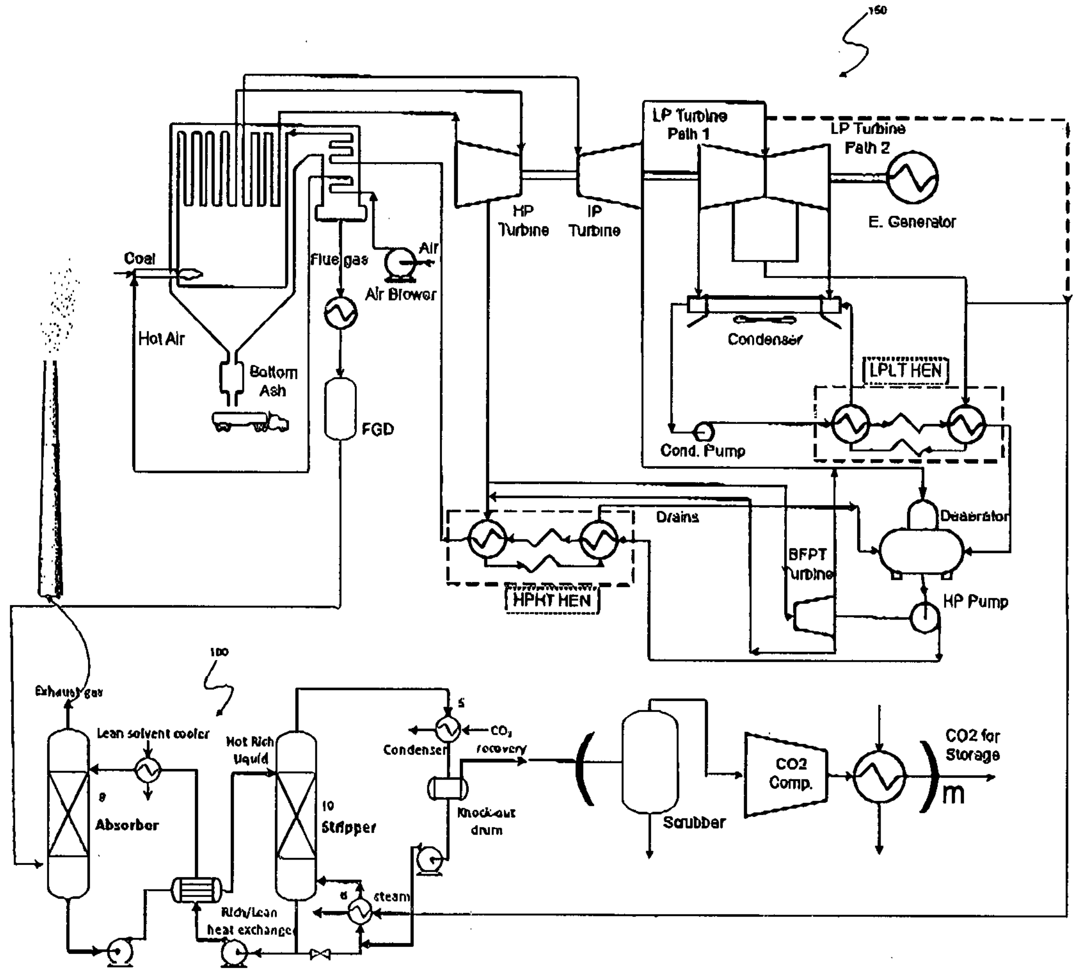
150
LP Turbine Path 1
LP Turbine Path 2
E. Generator
HP Turbine
IP Turbine
Coal
Air
Flue gas
Air Blower
Hot Air
Bottom Ash
FGD
Condenser
LPLT HEN
Cond. Pump
Deaerator
Drains
BFPT Turbine
HP Pump
HPHT HEN
100
Exhaust gas
Lean solvent cooler
Hot Rich Liquid
8
Absorber
10
Stripper
5
CO₂ recovery
Condenser
Knock-out drum
6
steam
Rich/Lean heat exchanger
Scrubber
CO2 Comp.
CO2 for Storage
m

Figure 4

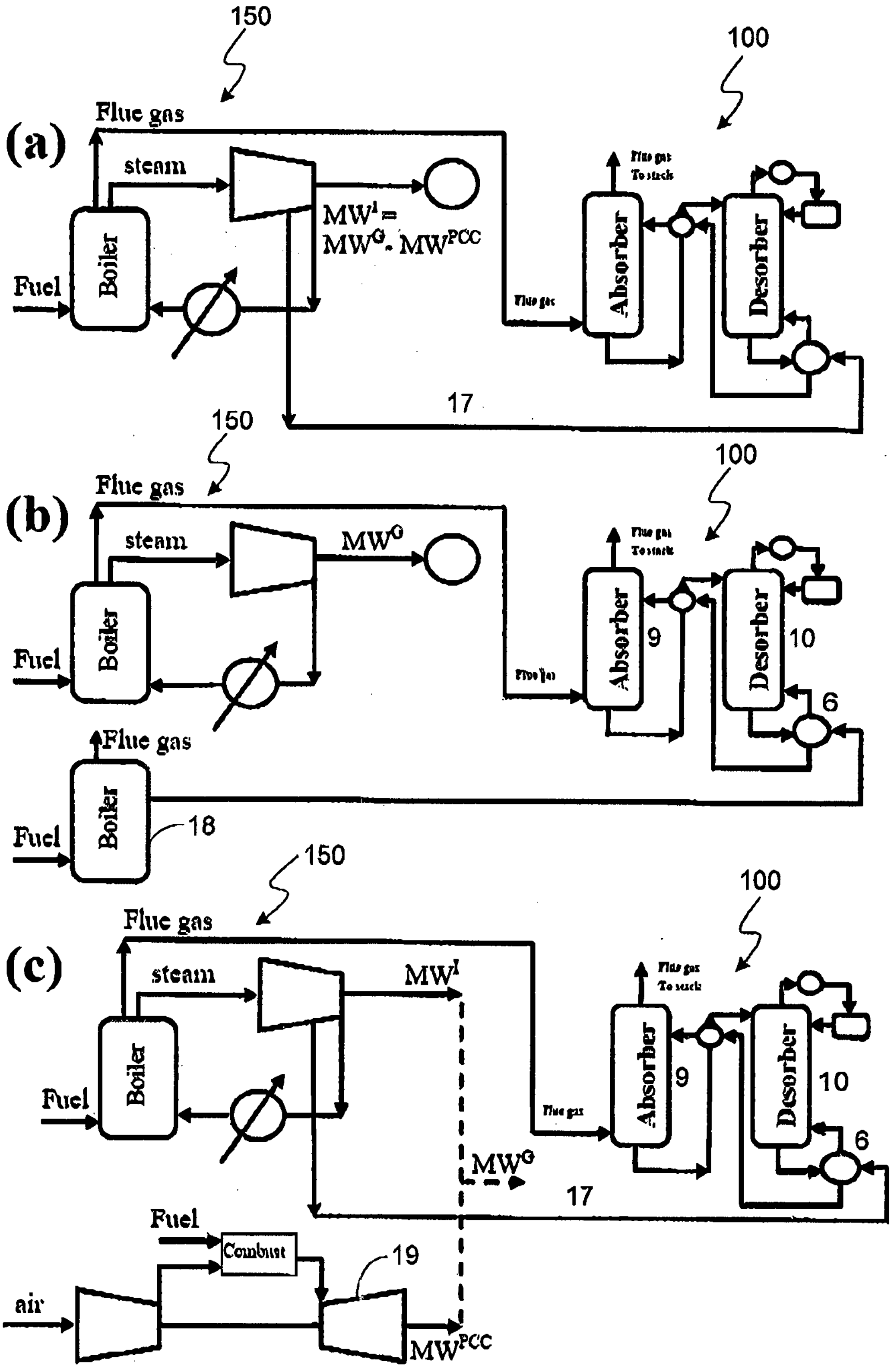
150
100
(a)
Flue gas
steam
$MW^I = MW^G - MW^{PCC}$
Fuel
Boiler
Flue gas To stack
Flue gas
Absorber
Desorber
17
150
100
(b)
Flue gas
steam
MW^G
Fuel
Boiler
Flue gas To stack
Flue gas
Absorber
9
Desorber
10
6
Flue gas
Fuel
Boiler
18
150
100
(c)
Flue gas
steam
MW^I
Fuel
Boiler
Flue gas To stack
Flue gas
Absorber
9
Desorber
10
6
MW^G
17
Fuel
Combust
19
air
MW^{PCC}

Figure 5

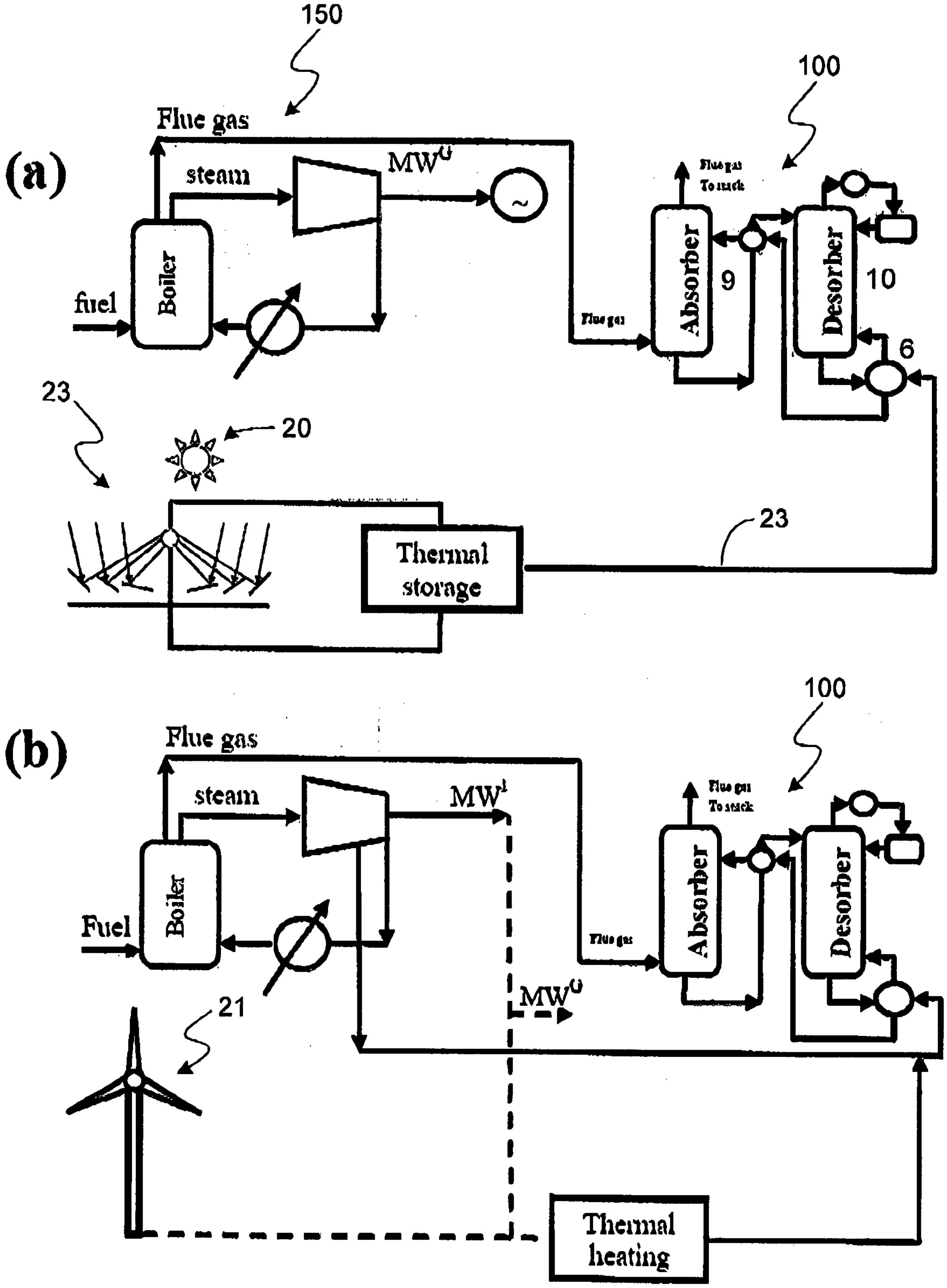
150
100
(a)
Flue gas
steam
MW^G
fuel
Boiler
Flue gas
To stack
Absorber
Desorber
9
10
6
Flue gas
23
20
23
Thermal storage
100
(b)
Flue gas
steam
MW^l
Fuel
Boiler
Flue gas
To stack
Absorber
Desorber
Flue gas
MW^G
21
Thermal heating

Figure 6

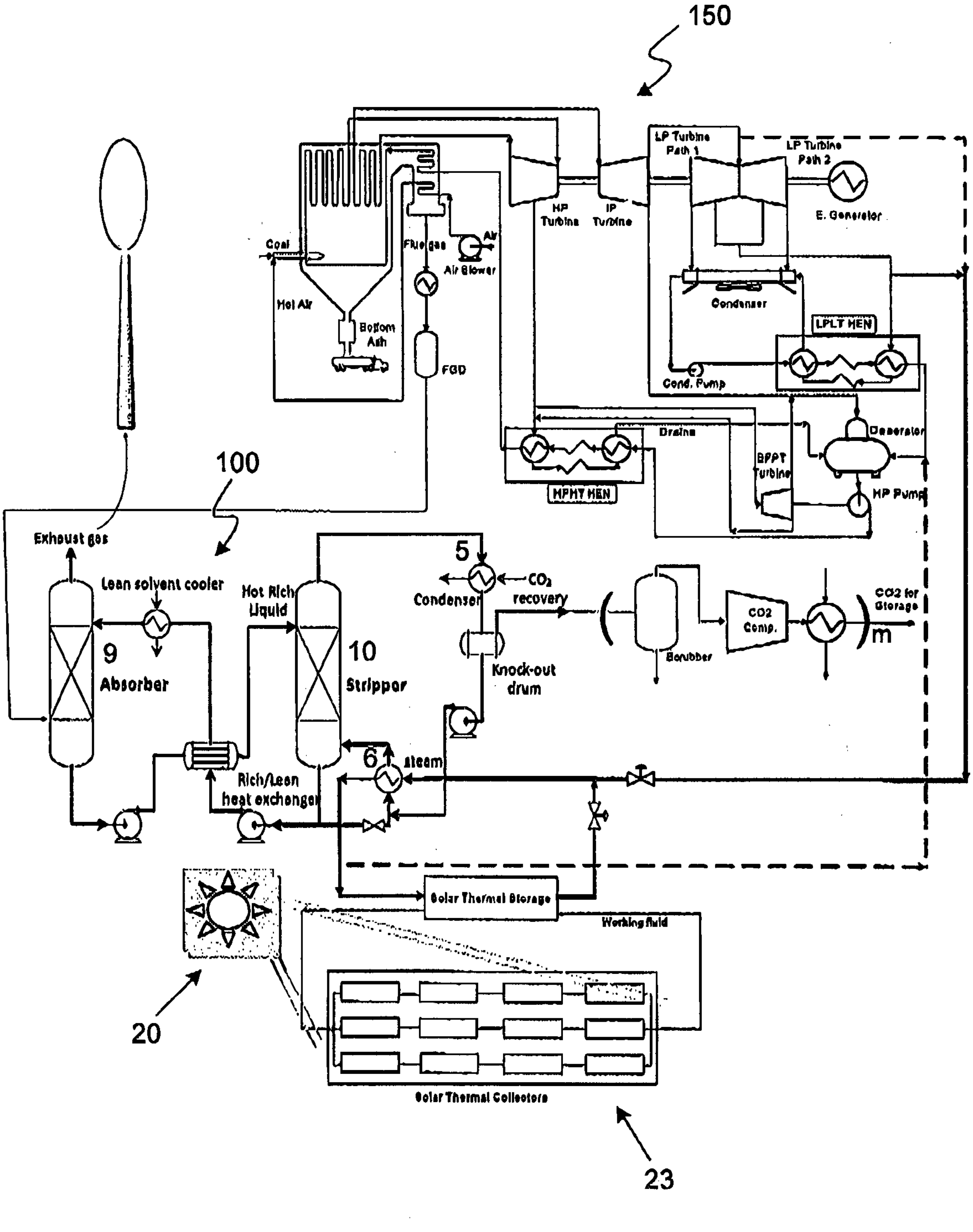
150
LP Turbine Path 1
LP Turbine Path 2
HP Turbine
IP Turbine
E. Generator
Coal
Flue gas
Air
Air Blower
Hot Air
Bottom Ash
FGD
Condenser
LPLT HEN
Cond. Pump
Drains
Deaerator
BFPT Turbine
HP Pump
MPHT HEN
100
Exhaust gas
Lean solvent cooler
Hot Rich Liquid
5
Condenser
CO₂ recovery
CO2 for Storage
Scrubber
CO2 Comp.
m
9
Absorber
10
Stripper
Knock-out drum
6
steam
Rich/Lean heat exchanger
Solar Thermal Storage
Working fluid
Solar Thermal Collectors
20
23

Figure 7

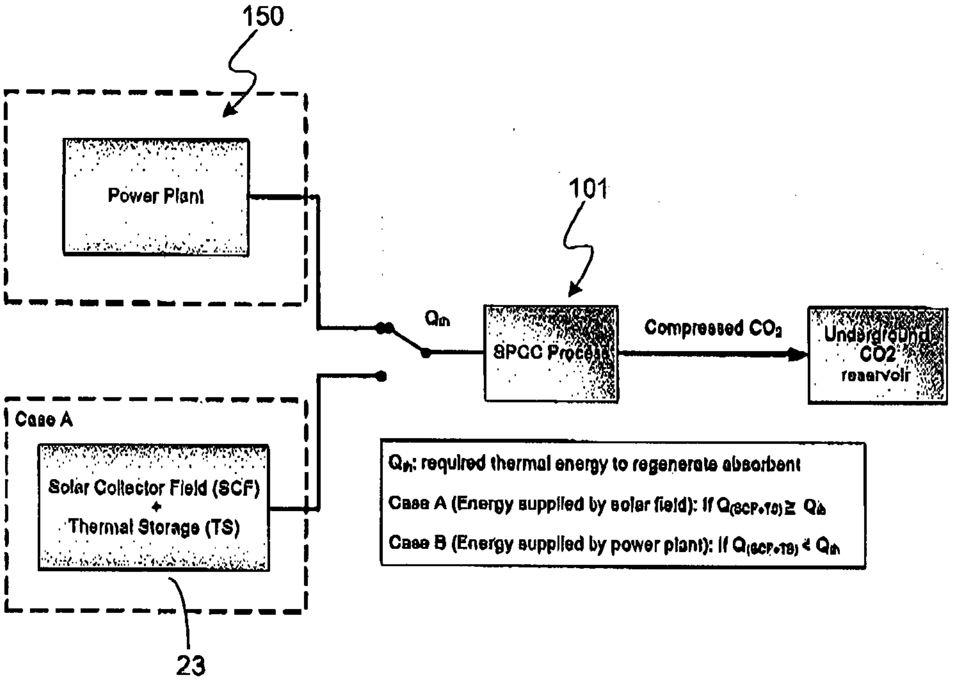

Figure 8

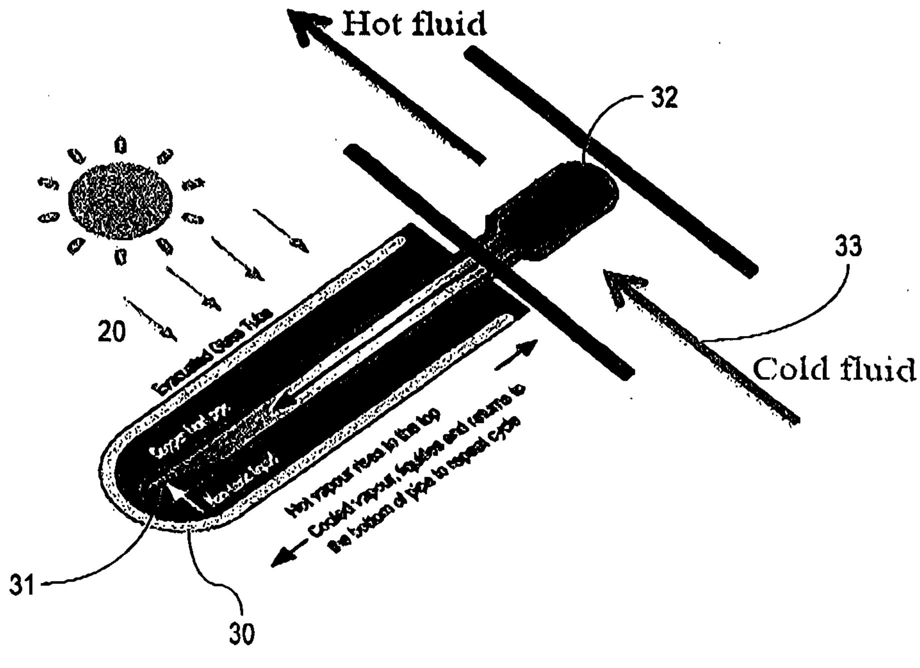

Figure 9

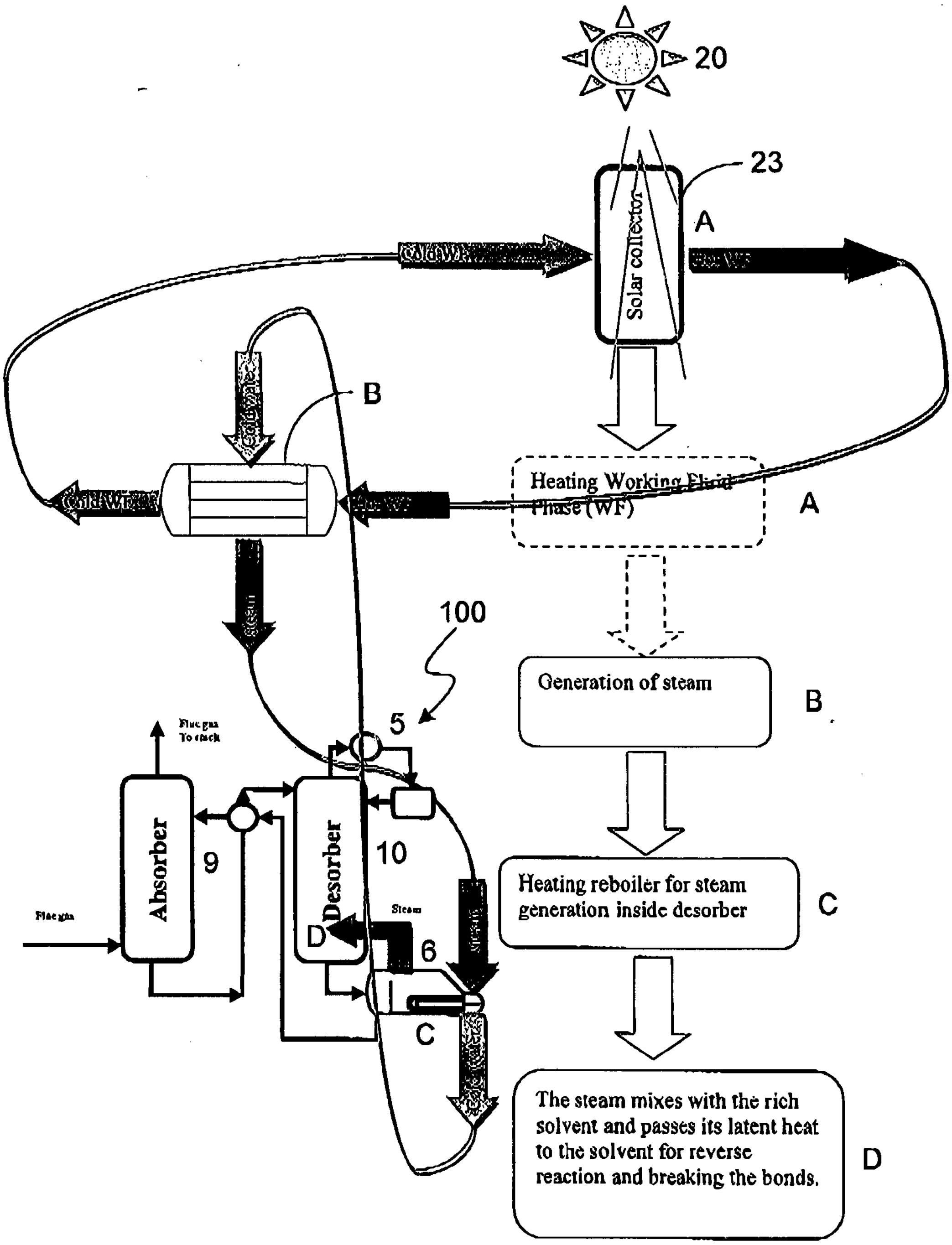
20
23
Solar collector
Cold WF
Hot WF
A
B
Heating Working Fluid Phase (WF)
A
Cold WF
Hot WF
Steam
100
5
Generation of steam
B
Flue gas To stack
Absorber
9
Desorber
10
Flue gas
Steam
D
6
Steam
Heating reboiler for steam generation inside desorber
C
C
The steam mixes with the rich solvent and passes its latent heat to the solvent for reverse reaction and breaking the bonds.
D

Figure 10

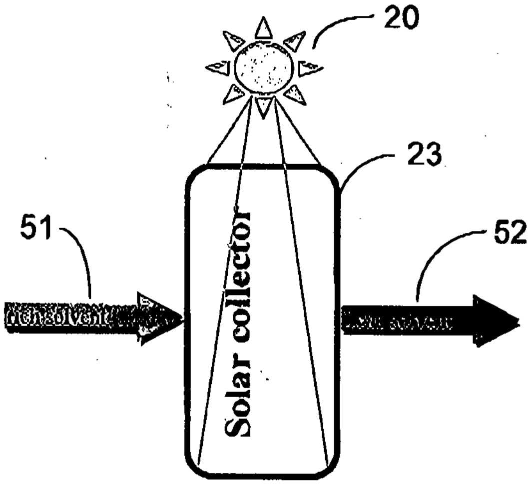

Figure 11

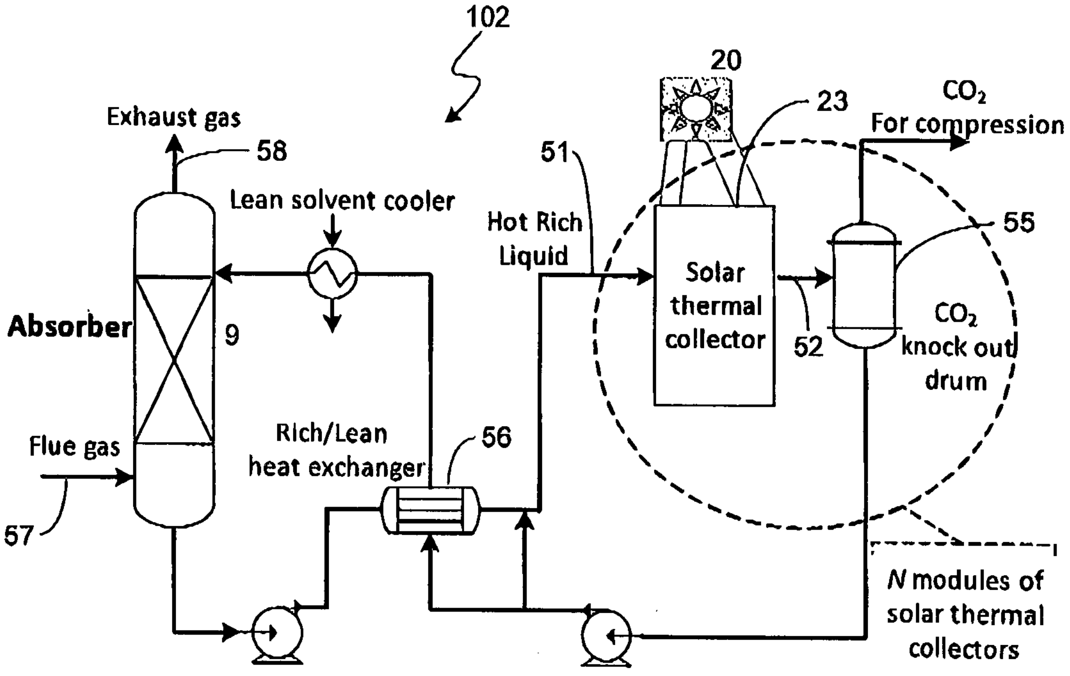

Figure 12

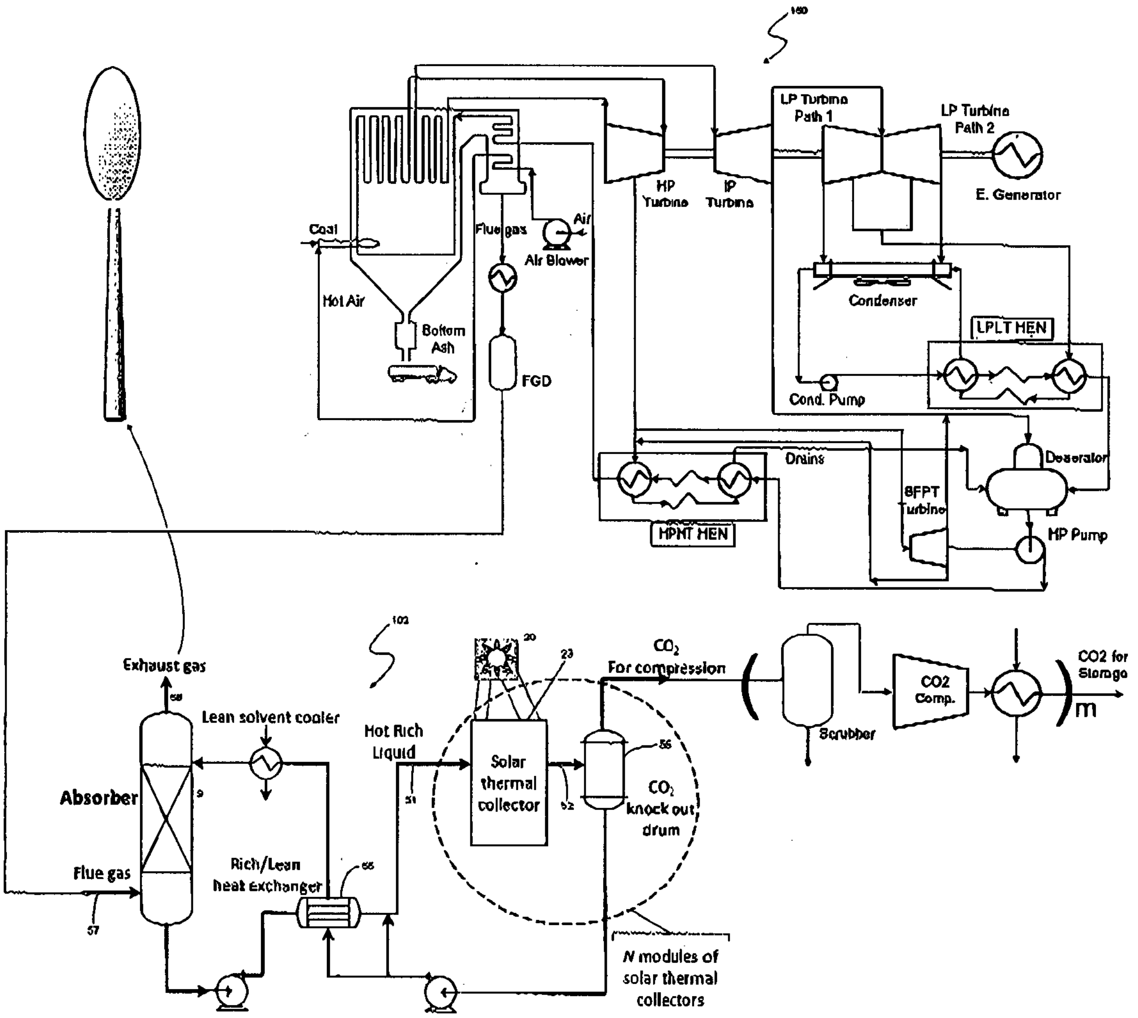
100
LP Turbine Path 1
LP Turbine Path 2
E. Generator
HP Turbine
IP Turbine
Coal
Flue gas
Air
Air Blower
Hot Air
Bottom Ash
FGD
Condenser
LPLT HEN
Cond. Pump
Deaerator
Drains
BFPT Turbine
HP Pump
HPHT HEN
102
20
23
CO2 For compression
Exhaust gas
58
Lean solvent cooler
Hot Rich Liquid
Absorber
9
Solar thermal collector
51
52
56
CO2 knock out drum
Flue gas
57
Rich/Lean heat exchanger
65
N modules of solar thermal collectors
Scrubber
CO2 Comp.
CO2 for Storage
m

Figure 13

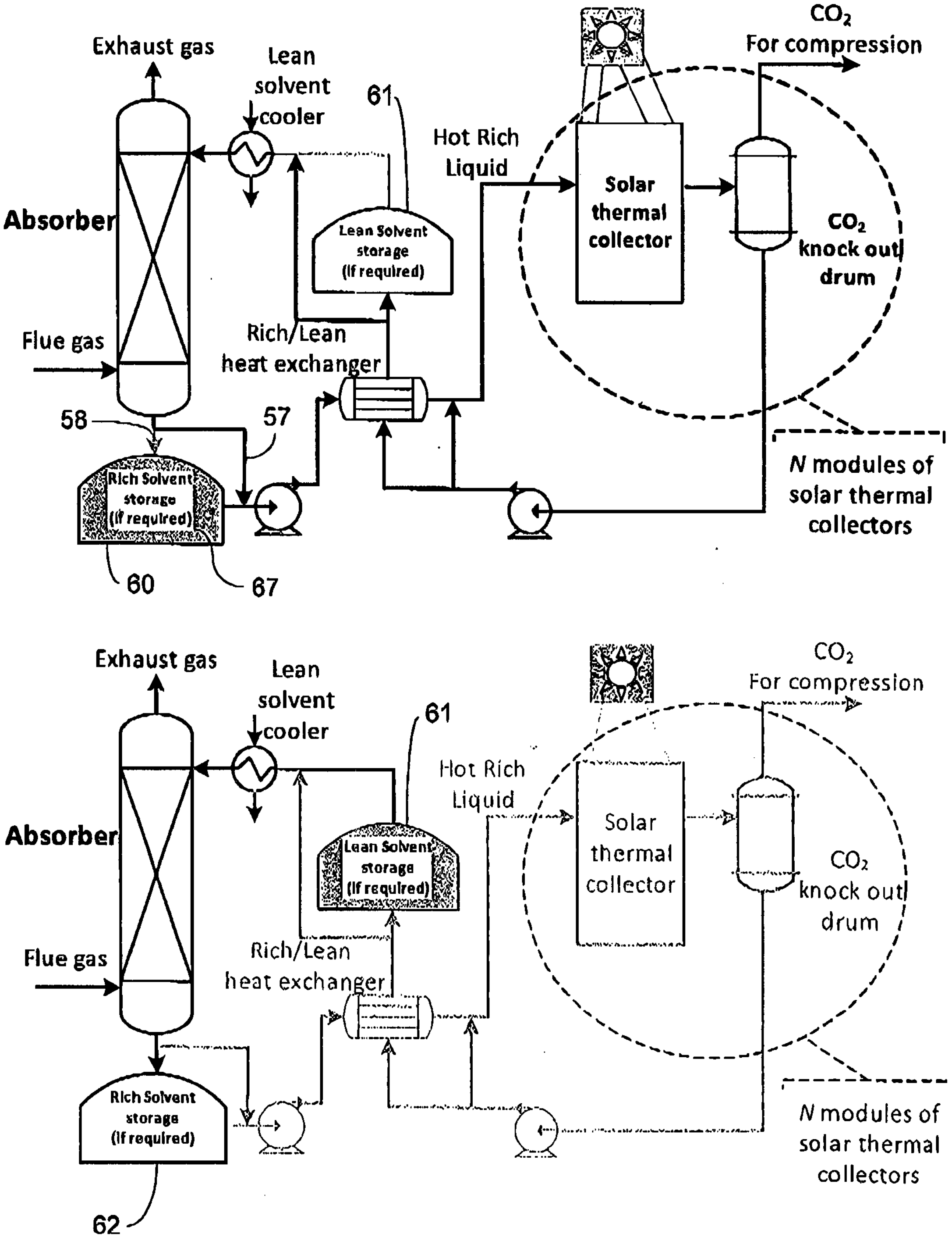
Exhaust gas
Lean solvent cooler
61
Hot Rich Liquid
CO_2 For compression
Absorber
Lean Solvent storage (If required)
Solar thermal collector
CO_2 knock out drum
Flue gas
Rich/Lean heat exchanger
58
57
Rich Solvent storage (If required)
N modules of solar thermal collectors
60
67
Exhaust gas
Lean solvent cooler
61
Hot Rich Liquid
CO_2 For compression
Absorber
Lean Solvent storage (If required)
Solar thermal collector
CO_2 knock out drum
Flue gas
Rich/Lean heat exchanger
Rich Solvent storage (If required)
N modules of solar thermal collectors
62

Figure 14

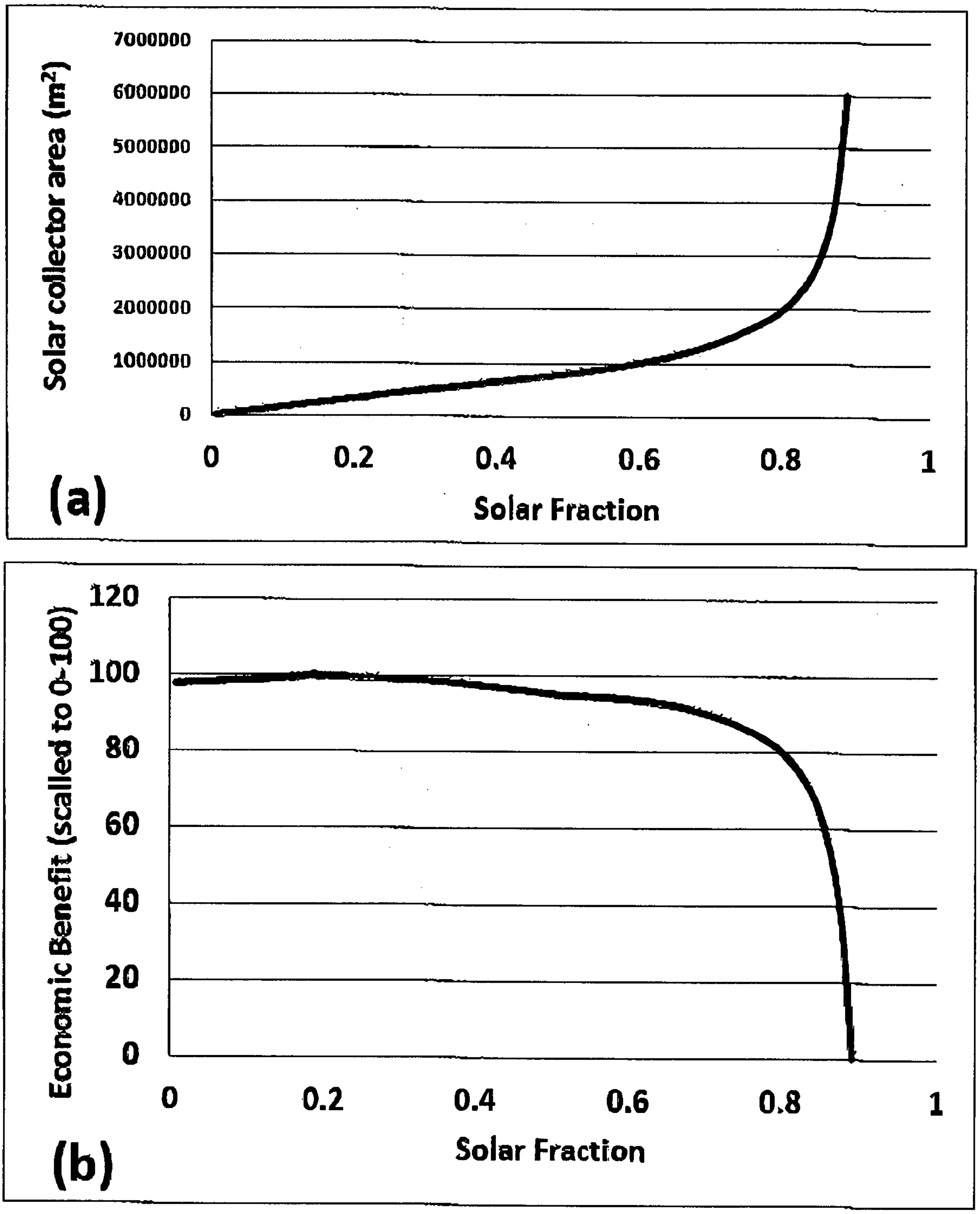
Solar collector area (m^2)
7000000
6000000
5000000
4000000
3000000
2000000
1000000
0
0
0.2
0.4
0.6
0.8
1
(a)
Solar Fraction
Economic Benefit (scalled to 0-100)
120
100
80
60
40
20
0
0
0.2
0.4
0.6
0.8
1
(b)
Solar Fraction

Figure 15

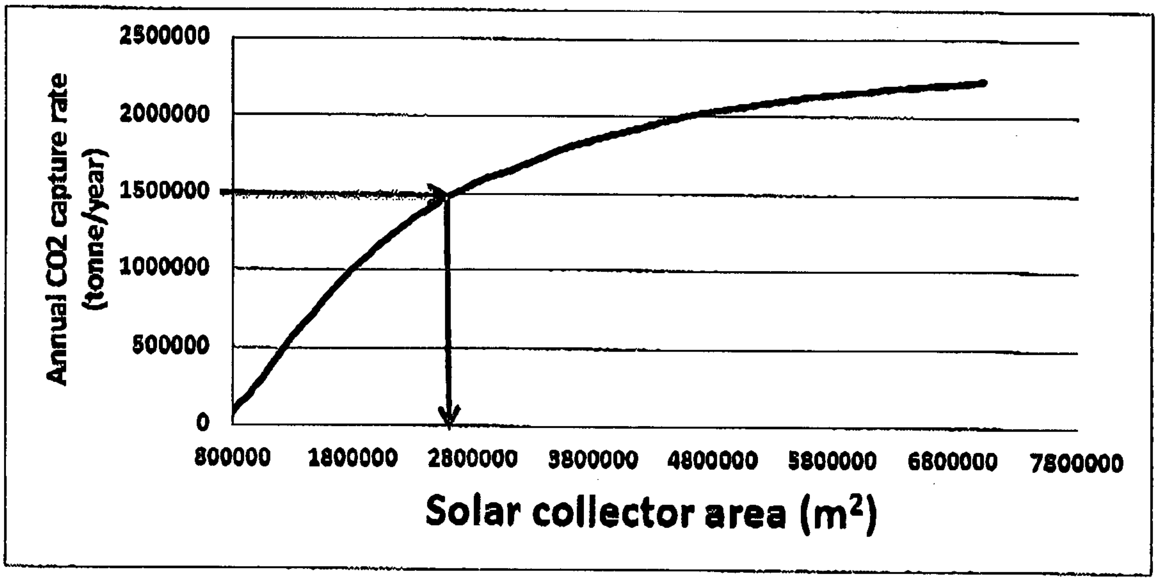

Figure 16

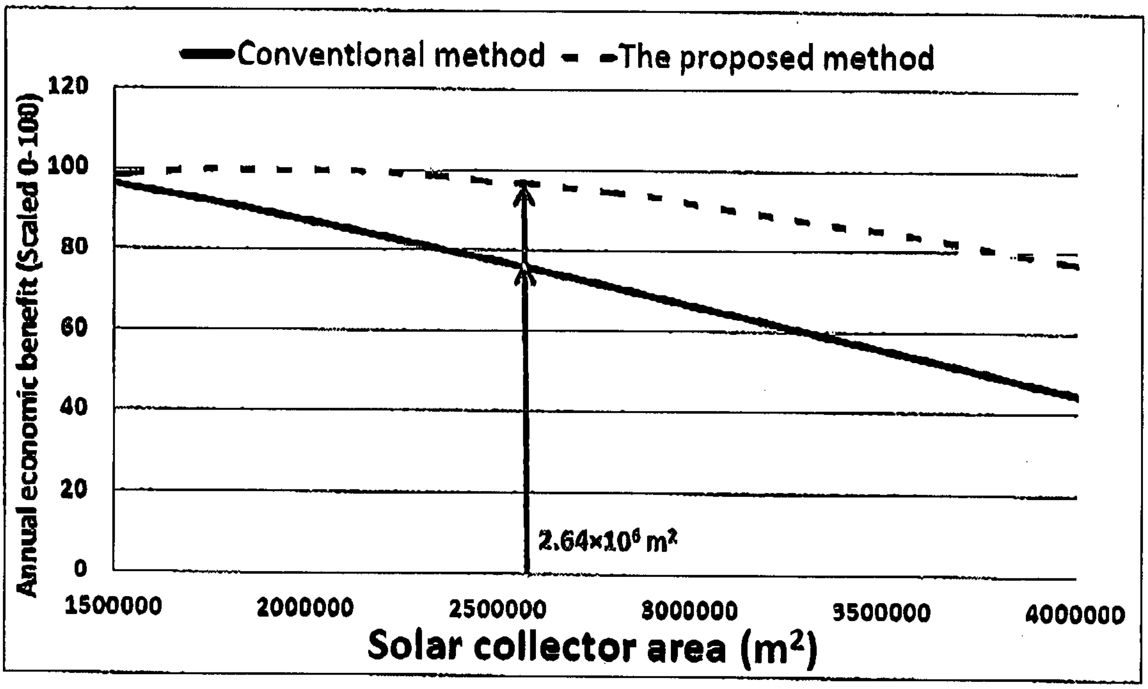

Figure 17

INTERNATIONAL SEARCH REPORT

International application No.
PCT/AU2014/000142

A. CLASSIFICATION OF SUBJECT MATTER

B01D 53/62 (2006.01) B01D 53/34 (2006.01) B01D 53/74 (2006.01)

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

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

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

WPI & EPODOC: IC/CC: B01D53/-, Y02C10/-, Y02E10/40, B01D2258/- & Keywords (Carbon dioxide, absorb, regenerator, sun, heat, radiation and similar terms); Espacenet & Google Patents: keywords (Carbon dioxide, CO2, absorption, absorb, adsorption, adsorb, regenerator, stripper, desorber, reboiler, sun, solar, heat, thermal, radiation, steam)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
	Documents are listed in the continuation of Box C	

☒ Further documents are listed in the continuation of Box C ☒ See patent family annex

* Special categories of cited documents:

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

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

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

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

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

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

"&" document member of the same patent family

Date of the actual completion of the international search
20 March 2014

Date of mailing of the international search report
20 March 2014

Name and mailing address of the ISA/AU

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Telephone No. 0262256151

INTERNATIONAL SEARCH REPORT

International application No.
PCT/AU2014/000142

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
	CN 201140032 Y (UNIV TSINGHUA [CN]) 29 October 2008	
X	abstract; page 1-3; figs. 1-4	1-4, 6-7, 9-10
Y	abstract; page 1-3; figs. 1-4	8
	US 2012/0192564 A1 (MISHIMA et al.) 02 August 2012	
X	abstract; para 0002; para 0010-0012; para 0018-22; para 0025; figs. 1-2	1-4
	WO 2012/173855 A2 (JOULE UNLIMITED TECHNOLOGIES, INC. [US/US]) 20 December 2012	
X	abstract; para 0045-0047; figs 1-3	2-3, 5
Y	abstract; para 0045-0047; figs 1-3	8

INTERNATIONAL SEARCH REPORT Information on patent family members	International application No. **PCT/AU2014/000142**

This Annex lists known patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document/s Cited in Search Report		**Patent Family Member/s**	
Publication Number	**Publication Date**	**Publication Number**	**Publication Date**
CN 201140032 Y	29 Oct 2008	None	
US 2012/0192564 A1	02 Aug 2012	AU 2012200504 B2	10 Oct 2013
		EP 2481895 A2	01 Aug 2012
		JP 2012158996 A	23 Aug 2012
		US 2012192564 A1	02 Aug 2012
WO 2012/173855 A2	20 Dec 2012	None	

End of Annex

Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001.