A circulating fluidized bed combustor arrangement includes (a) a circulating fluidized bed reactor in which (i) a combustion chamber combusts a fuel material in a suspension of solid particles of a circulating fluidized bed, (ii) a first cyclone separator arrangement receives a mixture of gases and solid particles from the combustion chamber for separating a first fraction of the solid particles from the exhaust gases, and (iii) a solid particle return system connected to the first cyclone separator arrangement in the exhaust gas flow path, (b) a heat transfer section including a water/steam heat exchanger section arranged after the first cyclone separator arrangement in the exhaust gas flow path, (c) a heat recovery device provided in connection with the combustion chamber, the first cyclone separator arrangement and the heat transfer section being arranged for recovering heat resulting from the combustion process in the combustion chamber, (d) a selective catalytic reduction system arranged in the exhaust gas flow path, after the heat transfer section, for removing NOx from the exhaust gas, (e) a device for injecting NOx reducing agent into the exhaust gases upstream of the selective catalytic reduction system, and (f) a second cyclone separator arrangement provided downstream of the first cyclone separator arrangement and upstream of the heat transfer section, in which a second fraction of the solid particles is separated from the exhaust gases.
FIG. 2
CIRCULATING FLUIDIZED BED COMBUSTOR AND A METHOD OF OPERATING A CIRCULATING FLUIDIZED BED COMBUSTOR

TECHNICAL FIELD AND BACKGROUND OF THE INVENTION

[0001] The present invention relates to a circulating fluidized bed combustor and a method of operating a circulating fluidized bed combustor. Further, it relates to a novel method of controlling NOx.

[0002] A circulating fluidized bed combustor arrangement of the prior art comprises a furnace, to which fuel, bed material and combustion air are introduced. When combustion of the fuel, heat is generated, and both ash and exhaust gases are formed. The exhaust gases are taken to a separator, which separates solid particles, including the bed material, from the gases, and returns the solid particles back to the furnace. It is distinctive to the combustion process that the oxidation reaction of the fuel material is intended to be as complete as possible. Thus, the flue gases or exhaust gases do not contain substantially any unburned material.

[0003] Structurally, the circulating fluidized bed (CFB) combustor generally includes a furnace having a bottom, side walls and a roof, and a particle separator connected in flow communication with the upper part of the furnace. At least some walls of the furnace are normally inclined in such a way that the cross section of the furnace increases upwardly, i.e., the part of the furnace having the inclined walls may be of a converging bottom part. In practice, all the walls and the roof of the boiler and the separator comprise water or steam tubes to collect heat from the furnace. The walls at the converging bottom part of the furnace are normally covered with refractory material that resists abrasion better than metallic water tube walls or steam tube walls. The bottom of the furnace is provided with a grid for introducing combustion or suspending or fluidizing gas, called primary air, into the furnace, and for removing ash and other debris from the furnace. The side walls of the furnace are provided with means for introducing fuel and means for introducing secondary air into the furnace, as well as to start-up burners. The furnace is also equipped with means for feeding bed material into the furnace. Very often, the introduction means (for fuel, secondary air, bed material) are positioned in the converging bottom part of the furnace.

[0004] The particle separator separates solid particles from exhaust gas-solid particles suspension entering the separator from the upper part of the furnace. The exhaust gases are taken for further treatment separated from the separator, and separated solid particles are recycled back to the lower part of the furnace via a recycling conduit, including a sealing device, like a seal point, the purpose of which is, e.g., to prevent gas flow from the furnace to the separator via the recycling conduit. This solid particles circulation is called an external circulation. In addition to vertical upward of exhaust gas-solid particles suspension in the furnace finally entering into the separator, there is a vertical downward of particles moved near and along the furnace walls. This solid particles circulation is called an internal circulation.

[0005] The exhaust gas resulting from a CFB combustor is released to the atmosphere, and, thus, it is an evident conclusion that the emissions of the exhaust gases including pollutants, such as NOx, SOx, etc., should be minimized, and the gases do not contain substantially any unburned material. The primary nitrogen pollutants produced by combustion are nitric oxide (NO) and nitrogen dioxide (NO₂). NOx is formed from the fuel combustion in a CFB combustor. Fuel nitrogen and nitrogen in air are the major sources of the pollutant formed at a temperature of 800-950°C in a CFB combustor. Since NOx is an atmospheric pollutant, regulations call for limiting its emission level into the atmosphere.

[0006] In practice, NOx is formed via three pathways, the first being fuel NOx from nitrogen in the fuel. It is produced when nitrogen in the fuel combines with the excess oxygen in the combustion air, and it is only a problem with fuel containing fuel bound nitrogen. Secondly, NOx is formed as so-called thermal NOx. Thermal NOx is produced when nitrogen and oxygen in the combustion air combine at high flame temperatures, say, about 950°C and above. Thirdly, a so-called prompt NOx is formed during the transitional phase of gas species in the fuel combustion. The fraction of prompt NOx in the exhaust gas is insignificant.

[0007] A CFB combustor is as such beneficial in view of NOx emissions due to the considerably low combustion temperature, which is typically below 950°C. However, currently allowable limits and particularly stringent emission control demands to be applied in the future call for further necessary measures to meet such demands.

[0008] Once formed, NOx emissions from a CFB combustor can be controlled in many ways. It is known from the prior art to utilize so-called Selective Non-Catalytic Reduction (SNCR) in connection with CFB combustors. The procedure involves the use of a reducing agent, such as ammonia (NH₃) or urea (CO(NH₂)₂) as an additive to be injected into the exhaust gases. These additives are injected into the hot exhaust gas stream at a temperature window of 750-950°C, at a nominal NH₃/NO molar ratio in excess of one, while maintaining the NH₃ slip at reasonably low levels. The NOx reduction is achieved by the following reactions:

Ammonia net reaction: \( \text{NH}_3 + \text{NO} + \frac{3}{2}\text{O}_2 \rightarrow \text{N}_2 + \frac{3}{2}\text{H}_2\text{O} \)

Urea net reaction: \( \text{CO(NH}_2)_2 + 2\text{NO} + \frac{5}{2}\text{O}_2 \rightarrow 2\text{N}_2 + \text{CO}_2 + 2\text{H}_2\text{O} \).

The NOx reduction efficiency with the SNCR-method generally ranges from about 20 to about 80%.

[0009] Another way of controlling NOx emissions is to use Selective Catalytic Reduction (SCR) process. This involves a catalytic reaction of NH₃ and NOx in the presence of a catalyst, such as vanadium pentoxide supported on a titanium dioxide substrate. NH₃ is injected upstream of the SCR catalyst and reduces NOx to nitrogen and water as the gases flow through the catalyst grid. The reaction temperature for NOx removal is much lower than the SCR, in the range of 300-500°C. The SCR process is highly efficient in removing NOx, and over 90% of the NOx may be removed through this process. The net reaction of the process is: \( \text{NH}_3 + \text{NO} + \frac{3}{4}\text{O}_2 \rightarrow \text{N}_2 + \frac{3}{2}\text{H}_2\text{O} \).

[0010] The external circulation of solid particles in CFB combustors is typically limited to substantially coarser particles than those particles that escape the capture and, thus, the capture efficiency of a commonly used particle separator allows an escape of particles through the separator to a certain extent, which may be denoted as dust loading. This particularly concerns particles of smaller size. This is typical, since CFB combustors use sorbent particles, such as limestone particles. Dust loading in CFB combustors is thus considerably high, much higher than that encountered in Pulverized Fuel (PF) combustion systems, being generally about 50-200% more than that in PF units firing similar fuels. With high ash, low heating value fuels, the dust load of the CFB combustors approaches much higher values. The dust load in the CFB systems depends on, among others, the fuel sulfur content, the sulfur capture capability of the limestone particles and the percentage of the sulfur removed in the circu-
lating fluidized bed. In addition, the fuel particle size in the CFB systems is much larger than that used in the PF systems. Thus, resulting in larger ash particles in the CFB systems. In the CFB systems, the mean fuel particle size is at least an order of magnitude larger. As evidence from the above analysis, these two major problem areas remain in the direct use of SCR in the CFB combustors: large ash particles and high dust loading.

[0011] U.S. Pat. No. 6,395,237 describes a circulating fluidized bed (CFB) combustor having a selective catalytic reduction (SCR) system employed downstream of the CFB combustor furnace. The CFB combustor is equipped with a primary particle separator, U.S. Pat. No. 6,395,237 further suggests to provide a multicyclone dust collector means as a secondary separator, located downstream of the at least one of the superheater and reheater heat transfer surfaces, for further separating solid particles from the flow of exhausted gas/solid particles. An SCR system is located downstream of the multicyclone dust collector means for removing NO\textsubscript{x} from the flow of exhaust gas/solid particles. The multicyclone dust collector must be, in practice, installed at a considerably low temperature environment due to its construction. Usually, the multicyclones are of a metal construction and, thus, limited in application at about 760°C and below for continuous operation.

[0012] U.S. Pat. No. 5,318,755 describes a method, in which hot flue or process gases are cleaned utilizing an apparatus containing a barrier filter module formed of a monolithic ceramic support structure coated with a thin porous ceramic layer having a pore size of about 0.01-0.5 microns, and a catalyst module formed of a support structure coated with a catalyst. The hot flue gases may be associated with a fluidized bed boiler plant, such as a circulating fluidized bed reactor. Gases to be cleaned are passed through the barrier filter module into contact with the thin porous ceramic layer, and then, through the catalyst module, so that there is a catalytic reaction with the gas. It also describes an arrangement, wherein gas cleaning at a high temperature is achieved using a honeycomb ceramic filter followed by a heat exchanger and then SCR catalyst shells.

SUMMARY OF THE INVENTION

[0013] An object of the present invention is to find at least one solution to at least one of the problems discussed above.

[0014] Another object of the present invention is to provide a circulating fluidized bed combustor that provides reduced amounts of pollutants to the atmosphere.

[0015] Yet another object of the present invention is to provide a method of operating a circulating fluidized bed combustor that provides reduced amounts of pollutants to the atmosphere.

[0016] The above and other objects of the present invention are met with a circulating fluidized bed combustor arrangement considering a circulating fluidized bed reactor having at least a combustion chamber for combusting a fuel material in a suspension of solid particles of a circulating fluidizing bed, a first cyclone separator arrangement arranged to receive a mixture of gases and solid particles from the combustion chamber for separating a first fraction of the solid particles from the exhaust gases, a solid particle return system connected between the first cyclone separator returning separated solid particles and maintaining an external circulation of the solid particles, and a heat transfer section comprised water/steam cooled heat transfer sections arranged after the first cyclone separator arrangement in the exhaust gas flow path. The circulating fluidized bed combustor arrangement further comprises a heat recovery means provided in connection with the combustion chamber, the first cyclone separator arrangement and the heat transfer section, arranged for recovering heat resulting from the combustion process in the combustion chamber, a selective catalytic reduction system arranged into the exhaust gas flow path after the heat transfer section for removing NO\textsubscript{x} from the exhaust gas, means for injecting NO\textsubscript{x} reducing agent into the exhaust gases upstream of the selective catalytic reduction system, and a second cyclone separator arrangement is provided downstream of the first cyclone separator arrangement in which a second fraction of the solid particles is separated from the exhaust gases.

[0017] The first cyclone separator arrangement is preferably arranged to separate the first fraction of the solid particles, which comprises, preferably, >98% of the particles contained by the gases.

[0018] Preferably, the second cyclone separator arrangement is provided immediately downstream of the first cyclone separator arrangement. In this way, the solid material may be separated from the exhaust gases at a high temperature, and the recycling of the particles back to the reactor are more feasible.

[0019] According to an embodiment of the invention, in the circulating fluidized bed combustor arrangement, the first cyclone separator arrangement comprises at least one cyclone separator arranged to separate particles having a diameter of >140 µm and the second cyclone separator arrangement comprises at least one cyclone separator arranged to separate particles primarily having a diameter of >20-40 µm. Preferably, the first cyclone separator arrangement is connected to the combustion chamber of the circulating fluidized bed combustor arrangement for recycling separated solid particles back to the combustor, and the second cyclone separator arrangement is connected to a further processing system of solid particles.

[0020] According to a preferred embodiment of the invention, the first cyclone separator arrangement and the second cyclone separator arrangement are connected to a combustion chamber of the circulating fluidized bed combustor arrangement for recycling separated solid particles back to the combustor.

[0021] Accordingly to a further embodiment of the present invention, the circulating fluidized bed combustor includes a desulfurization system in connection with the combustion chamber, which includes means for injecting sulfur sorbent material into the combustion chamber, and the second cyclone separator arrangement is connected to a combustion chamber of the circulating fluidized bed combustor arrangement for recycling separated sulfur sorbent material back to the combustor.

[0022] Preferably, the means for injecting ammonia into the exhaust gases is arranged immediately upstream of the selective catalytic reduction system.

[0023] According to an embodiment of the invention, the first cyclone separator arrangement consists of one cyclone separator and the second cyclone separator arrangement connected to the first cyclone separator arrangement consists of two cyclone separators.

[0024] Preferably, the selective catalytic reduction system for removing NO\textsubscript{x} comprises a group of parallel flow channels having catalytic material on its surface.

[0025] According to the present invention, a preferred method of operating a circulating fluidized bed combustor arrangement includes the steps of at least:

[0026] combusting fuel material in a combustion chamber of a circulating fluidized bed reactor in a suspension of solid particles of a circulating fluidized bed,
passing a mixture of gases and solid particles from the combustion chamber to a first cyclone separator arrangement and separating a first fraction of the solid particles from the gases,

returning solid particles separated in the first cyclone separator arrangement via a solid particle return system from the first cyclone separator to the combustion chamber and maintaining an external circulation of the solid particles, and

passing the gases from which the first fraction of the solid particles has been separated further in the process as exhaust gases,

recovering heat from the exhaust gases at least to a steam super heater section and/or economizer section after the first cyclone separator arrangement in the exhaust gas flow path, to heat recovery means provided in connection with the combustion chamber, to the first cyclone separator,

reducing NOx from the exhaust gas by passing the exhaust gas through a selective catalytic reduction system arranged in the exhaust gas flow path, after recovering from the exhaust gases,

injecting ammonia into the exhaust gases upstream of the selective catalytic reduction system,

and wherein

a second fraction of the solid particles is separated from the exhaust gases in a second cyclone separator arrangement provided downstream of the first cyclone separator arrangement prior to reducing NOx from the exhaust gases. Thus, the exhaust gases are passed through the second cyclone separator without substantial cooling.

Preferably, the first cyclone separator arrangement comprises at least one cyclone separator in which particles having a diameter of >140 μm are separated from the exhaust gases and in the second cyclone separator arrangement comprising at least one cyclone separator, in which, preferably, particles having a diameter of >20-40 μm are separated from the exhaust gases.

Preferably, the solid particles separated in the first cyclone separator arrangement are recycled back to the combustion chamber of the circulating fluidized bed combustor, and the solid particles separated in the second cyclone separator arrangement are at least partially passed to a further processing system of solid particles.

According to an advantageous embodiment of the invention, the solid particles separated in the first cyclone separator arrangement and the second cyclone separator arrangement are at least partially recycled back to the combustion chamber of the circulating fluidized bed combustor.

According to another advantageous embodiment of the invention, sulfur sorbent material is injected into the combustion chamber of the circulating fluidized bed combustor, and unreacted sulfur sorbent material is separated in the second cyclone separator arrangement and processed and/or recycled at least partially back to the combustor.

According to a preferred embodiment of the invention, ammonia is injected into the exhaust gases immediately upstream of the selective catalytic reduction system.

According to yet another embodiment of the invention, a method of operating a circulating fluidized bed combustor arrangement includes the steps of at least:

combusting fuel material in a combustion chamber of a circulating fluidized bed reactor in a suspension of solid particles of a circulating fluidized bed, passing a mixture of gases and solid particles from the combustion chamber to a first cyclone separator arrangement and separating a first fraction of the solid particles from the gases,

returning solid particles separated in the first cyclone separator arrangement via a solid particle return system from the first cyclone separator to the combustion chamber and

passing the gases from which the first fraction of the solid particles has been separated further in the process as exhaust gases,

recovering heat from the exhaust gases in a water/steam heat exchanger section arranged after the first cyclone separator arrangement in the exhaust gas flow path, wherein

a second fraction of the solid particles is separated from the exhaust gases in a second cyclone separator arrangement provided downstream of the first cyclone separator arrangement prior to recovering heat from the exhaust gases,

ammonia is injected into the exhaust gases upstream of the selective catalytic reduction system,

NOx is removed from the exhaust gas in an SNCR process by reacting a first portion of the ammonia injected,

NOx is removed from the exhaust gas in an SCR process by passing the exhaust gas through a selective catalytic reduction system arranged into the exhaust gas flow path after recovering from the exhaust gases and reacting a second portion of the ammonia injected, and

sulfur sorbent material is injected into the combustion chamber of the circulating fluidized bed combustor, and unreacted sulfur sorbent material is separated in the second cyclone separator arrangement and recycled at least partly back to the combustor.

Preferably, heat from the exhaust gases is recovered after passing the second cyclone separator, so that the selective catalytic reduction system is operated at 450-500 °C.

Other features of the present invention can be seen in the appended claims and the following description of the drawings.

Several potential problems may be avoided with the present invention. The present invention provides a more reliable operation of the CFB combustor, e.g., because catalyst plugging due to a high dust load and alkalinity of ash may be eliminated or considerably reduced. With the present invention, it is also possible to minimize ash deposits which react with ambient moisture and develop hard deposits and acidity, thereby damaging the base material of the catalyst grid. Also, permanent plugging of the channels and pores may be avoided and/or the lifetime of the SCR catalysts is considerably increased.

BRIEF DESCRIPTION OF THE DRAWINGS

In the following, the wall construction of the present invention will be discussed in more detail with reference to the following drawings, in which:

FIG. 1 is a schematic representation of a circulating fluidized bed combustor arrangement of a first embodiment of the present invention,

FIG. 2 is a schematic representation of a circulating fluidized bed combustor arrangement of a second embodiment of the present invention, and
FIG. 3 is a schematic representation of a circulating fluidized bed combustor arrangement of a third embodiment of the present invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIG. 1 schematically illustrates a circulating fluidized bed (CFB) combustor arrangement 10. The CFB combustor arrangement 10 comprises a circulating fluidized bed reactor 12 including a combustion chamber 14, in which fuel material may be combusted making use of a circulating bed of solid particles therein. The CFB reactor 12 is provided with numerous auxiliary devices, of which only those necessary for understanding the invention are described herein. The CFB reactor is connected at its upper portion to a cyclone separator arrangement 16, which acts as a primary separation stage. In the embodiment of FIG. 1, the cyclone separator arrangement 16 includes one cyclone separator, but, e.g., in larger CFB reactors, there may be several separators installed in parallel. The cyclone separator 16 is connected to the lower portion of the combustion chamber 14 via a return conduit 18, including a cooling device, like a loop seal, the purpose of which is, e.g., to prevent gas flow from the combustion chamber 14 to the cyclone separator via the recycling conduit. The cyclone separator separates most of the solid particles from exhaust gas-solid particles entering the separator from the upper part of the combustion chamber 14. The exhaust gases are taken for further treatment from the separator, as will be explained later, and the separated solid particles are recycled back to the lower part of the combustion chamber 14 via the return conduit 18. This solid particles circulation is called an internal circulation. In addition to vertical upflow of exhaust gas-solid particles in suspension in the combustor finally entering into the separator inlet, there is a vertical downflow of particles near and along the combustor walls. This solid particles circulation is called the internal circulation.

The circulating fluidized bed combustor arrangement 10 is operated preferably so that fuel material is combusted in a combustion chamber of a circulating fluidized bed reactor in a suspension of solid particles of a circulating fluidized bed. The exhaust gases resulting from the combustion and solid particles are passed from the combustion chamber to a first cyclone separator arrangement, and a first fraction of the solid particles separated from the gases and solid particles separated in the first cyclone separator arrangement are returned via a solid particle return system from the first cyclone separator to the combustion chamber, and an external circulation of the solid particles is maintained.

Preferably, the primary separation stage, i.e., the first cyclone separator arrangement, is arranged to separate a first fraction of the solid particles from the exhaust gases having a diameter of preferably 120-140 μm and greater. This way, the operation of the circulating fluidized bed combustor may be maintained so that advantageously sized bed material is used. It is distinctive to the combustion process that the oxidation reaction of the fuel material is intended to be as complete as possible. Thus, the exhaust gases do not contain substantially any unburned material. Thus, the major concerns of the contents of the exhaust gases are of an environmental nature.

A circulating fluidized bed combustor arrangement according to the embodiment of FIG. 1 further comprises a heat transfer section 22 arranged downstream of the primary separation stage 16, in the flow direction of the exhaust gas in the arrangement. The heat transfer section 22 preferably comprises a steam super heater section 24 and/or an economizer section 26 arranged downstream of the first cyclone separator arrangement 16. Additionally, since the circulating fluidized bed combustor is intended to combust fuel, there are heat recovery means provided at least in connection with the combustion chamber 14, in order to recover the heat. The circulating fluidized bed combustor further comprises heat recovery means in connection with the first cyclone separator arrangement 16, and the heat transfer section 22, arranged for recovering heat resulting from the combustion process in the combustion chamber, and maintaining the construction at an acceptable temperature level. The combustion chamber is preferably constructed of a so-called membrane wall, in which steam generation tubes are joined together, forming a heat transfer wall. Additionally, the combustion chamber may be provided with internal heat transfer walls 32, such as a steam super heater.

The circulating fluidized bed combustor comprises a selective catalytic reduction (SCR) system 28. It is arranged in the exhaust gas flow path after the heat transfer section, in order to remove NOx from the exhaust gas. There are also means 34 for injecting NOx reducing agent into the exhaust gases upstream of the selective catalytic reduction system 28. The means for injecting the NOx reducing agent is connected to a source 36 of the agent. Preferably, the NOx reducing agent is ammonia, NH3. Thus, the SCR process involves the catalytic reaction of NH3 and NOx in the presence of a catalyst, such as vanadium pentoxide supported on a titanium dioxide substrate. NH3 is injected upstream of the catalyst and reduces NOx to nitrogen and water as the gases flow through the catalyst grid.

The method of operating a circulating fluidized bed combustor further comprises the steps of passing the gases from which the first fraction of the solid particles has been separated further in the process as exhaust gases, recovering heat from the exhaust gases at least to a steam super heater section and/or an economizer section after the first cyclone separator arrangement in the exhaust gas flow path, to heat recovery means provided in connection with the combustion chamber, to the first cyclone separator, removing NOx from the exhaust gas by passing the exhaust gas through a selective catalytic reduction system arranged in the exhaust gas flow path after recovering from the exhaust gases, and injecting ammonia into the exhaust gases upstream of the selective catalytic reduction system.

The reaction temperature for NOx removal is in the range of 300-500°C. The SCR process is highly efficient in removing NOx, and over 90% of the NOx may be removed through this process.

The selective catalytic reduction system 28 is a unit in which the contact area between the exhaust gas and the catalyst is remarkably high. In practice, the unit comprises a multi-channel system in which a large amount of parallel conduits covered with the catalyst is provided, and in which each conduit has a substantially small cross-sectional area being prone to clogging by accumulation of solid particles.

Now, between the first cyclone separator arrangement 12 and the selective catalytic reduction system 28, a second cyclone separator arrangement 10 is provided for separating a second fraction of solid particles from the exhaust gases before the exhaust gas is substantially cooled. The second cyclone separator arrangement is a so-called hot gas cyclone separator arranged to operate at high temperatures. In other words, the second cyclone separator is arranged to separate solid particles from exhaust gas being at a temperature of 800-950°C. In the embodiment of FIG. 1, the second cyclone separator arrangement 10 is provided with cooling means 38 which, in this case, comprises walls of a cooled structure for maintaining the temperature of the
cyclone construction at a desired level. Also, the first cyclone separator arrangement in the embodiment of FIG. 1 comprises similar cooling means 40 and it is also a so-called hot gas cyclone separator.

The second cyclone separator arrangement 10 primarily comprises, in the embodiment of FIG. 1, a single cyclone separator, which has its inlet 10.1 directly connected to an outlet 16.2 of the first cyclone separator arrangement 16. Thus, the exhaust gases and the solid particles not separated from the gases in the first cyclone separator arrangement are let to the second cyclone separator arrangement 10. The second cyclone separator arrangement 10 comprises at least one cyclone separator arranged to separate particles of a diameter of 20-40 μm and greater.

The second cyclone separator arrangement 10 comprises a solids outlet 10.3, through which the separated solid particles are removed from the cyclone. In the embodiment of FIG. 1, the separated fraction of solid particles, which is separated from the hot exhaust gases, is led to a further processing system of solid particles. The still substantially uncooled exhaust gases, from which the solid particles are already separated, are led via an outlet 10.2 of the second cyclone separator arrangement 10 to the heat transfer section 22. In the heat transfer section 22, the gases are first cooled to a temperature in the range of 300-500°C, after which, the exhaust gases are subjected to the NOX removal in the SCR process practiced in the selective catalytic reduction (SCR) system 28. NOX reducing agent is injected into the exhaust gases through the means 34 upstream of the selective catalytic reduction system 28.

In FIG. 2, there is shown another embodiment of the invention. It is, in many aspects, similar to that of FIG. 1 and, therefore, corresponding reference numbers have been used for corresponding elements and/or features. Also, FIG. 2 schematically illustrates a circulating fluidized bed (CFB) combustor arrangement 10 comprising a circulating fluidized bed reactor 12, including a combustion chamber 14, in which fuel material may be combusted making use of a circulating bed of solid particles therein. The combustion chamber 14 of the CFB reactor is connected at its upper portion to a cyclone separator arrangement 16, which acts as a primary separation stage. Also, in the embodiment of FIG. 2, the cyclone separator arrangement 16 includes one cyclone separator. The cyclone separator 16 is connected to the lower portion of the combustion chamber 14 via a return conduit 18, including a sealing device 20, such as a loop seal, the purpose of which is, e.g., to prevent gas flow from the combustion chamber 14 to the cyclone separator via the recirculating conduit. The cyclone separator 16 separates solid particles from exhaust gas-solid particles suspension entering the separator 16 from the upper part of the combustion chamber 14. The exhaust gases are taken for further treatment from the separator, as will be explained later, and the separated solid particles are recycled back to the lower part of the combustion chamber 14 via the return conduit 18. This solid particles circulation is called an external circulation. In addition to the vertical upflow of exhaust gas-solid particles suspension in the combustor entering finally into the separator inlet, there is a vertical downflow of particles near and along the combustor walls. This solid particles circulation is called the internal circulation.

In the embodiment shown in FIG. 2, the circulating fluidized bed combustor arrangement is provided with a combination of a so-called flue gas desulfurization (FGD) process and an SCR process. The combustion chamber 14 of the circulating fluidized bed reactor is provided with SOX sorbent feeding means 44 for feeding SOX sorbent into the circulating fluidized bed. Preferably, the SOX sorbent is limestone or a like substance, which captures sulfur from the exhaust gases.

In the circulating fluidized bed combustor, limestone, or dolomite is added into the bed for sulfur capture at substantially atmospheric conditions, the first step in the sulfur capture process is the calcination of CaCO₃, by reaction CaCO₃(s) → CaO(s) + CO₂(g). The calcination process proceeds significantly faster than the next step, which is the sulfur capture step, called the sulfation reaction: CaO(s) + SO₂(g) + ½O₂(g) → CaSO₄(s). It is beneficial for the FGD process and the reactions that the limestone and its successors (FGD-related particles) are substantially fine grained.

Preferably, the primary separation stage, i.e., the first cyclone separator arrangement is arranged to separate a first fraction of the solid particles from the exhaust gases having a diameter of 140 μm and greater. The limestone is fed into the combustor having such a particle size that a portion of the FGD-related particles are separated from the exhaust gases in the first cyclone separator arrangement 16. A second portion of the FGD-related particles is passed through the first cyclone separator arrangement 16 still being maintained at a suitable temperature for the FGD-process. While the FGD-related particles are passed through the first cyclone separator arrangement 16, they are simultaneously subjected to vigorous mixing, enhancing the reactions.

Prior to substantially cooling the exhaust gases, fine particles are also separated from the exhaust gases by means of the second cyclone separator arrangement 10. This simultaneously separates from the exhaust gases the FGD-related particles and other particles harmful to the operation of the SCR process. Since the second fraction of solid particles are separated from the exhaust gases before the exhaust gas is substantially cooled, the recycling of the particles back to the reactor 14 has a smaller cooling effect.

The second cyclone separator arrangement is a so-called hot gas cyclone separator arranged to operate at high temperatures. In other words, the second cyclone separator is arranged to separate solid particles from exhaust gas being at a temperature of 800-950°C. In the embodiment of FIG. 2, the second cyclone separator arrangement 10 is of an uncooled construction, enduring the high temperature circumstances.

The second cyclone separator arrangement 10 also comprises, in the embodiment of FIG. 2, a single cyclone separator arranged to separate particles of a diameter primarily of about 20-40 μm and greater. This way, the entrance of solid particles to the SCR system 28 is substantially prevented. The second cyclone separator arrangement comprises a solid outlet 10.3 through which the separated solid particles may be removed from the cyclone. In the embodiment of FIG. 2, the second fraction of solid particles, which is separated from the hot exhaust gases, may be partially or completely recycled back to the reactor 14 via a recirculation conduit 46. This makes it possible to maintain a circulation of finely divided bed material, including FGD-related particles, such as limestone.

In FIG. 3, yet another embodiment of the invention is shown. It is in most aspects similar to that of FIG. 1 and FIG. 2 and, therefore, corresponding reference numbers have been used for corresponding elements and/or features. The only difference from the embodiment of FIG. 2 is that the second cyclone separator arrangement 10 comprises two parallel cyclone separators 10, the other of which is depicted with a dashed line. There is also shown an alternative or additional location for means 34 for injecting NOX reducing agent into the exhaust gases upstream of the first cyclone separator arrangement. Thus, according to an embodiment of
the invention, in the method of operating a circulating fluidized bed combustor, both SNCR and SCR systems are employed to achieve maximum NOx reduction efficiency. Additionally, according to a further advantageous embodiment of the invention, the circulating fluidized bed combustor arrangement is provided with/executes a combined FGD-process, an SCR-process and an SNCR-process, each being separately described above. This provides a circulating fluidized bed combustor, in which both NOx and SOx emissions may be reduced to a level meeting the strictest of requirements.

In view of the above description, it has to be understood that only a few most preferred embodiments of the present invention has been discussed. Thus, it is obvious that the invention is not limited to only the embodiments discussed above, but that it can be modified in many ways within the scope of the appended claims. It has to be understood, also, that features of a specific embodiment of the invention may be applied in connection with features of other embodiments within the basic idea of the present invention, or that features from different embodiments may be combined, as long as they result in a working and technically feasible construction.

1. A circulating fluidized bed combustor arrangement comprising:
   (a) a circulating fluidized bed reactor comprising:
      (i) a combustion chamber for combusting a fuel material in a suspension of solid particles of a circulating fluidized bed;
      (ii) a first cyclone separator arrangement arranged to receive a mixture of gases and solid particles from the combustion chamber for separating a first fraction of the solid particles from the exhaust gases; and
      (iii) a solid particle return system connected to the first cyclone separator for returning separated solid particles to the combustion chamber;
   (b) a heat transfer section comprising a water/steam heat exchanger section arranged after the first cyclone separator arrangement in a flow path of the exhaust gases;
   (c) heat recovery means, provided in connection with the combustion chamber, the first cyclone separator arrangement and the heat transfer section, being arranged for recovering heat resulting from the combustion process in the combustion chamber;
   (d) a selective catalytic reduction system arranged in the flow path of the exhaust gases, after the heat transfer section, for removing NOx from the exhaust gas;
   (e) means for injecting NOx reducing agent into the exhaust gases upstream of the selective catalytic reduction system; and
   (f) a second cyclone separator arrangement provided downstream of the first cyclone separator arrangement and upstream of the heat transfer section, in which a second fraction of the solid particles is separated from the exhaust gases.

2. A circulating fluidized bed combustor arrangement according to claim 1, wherein the second cyclone separator arrangement is provided immediately downstream of the first cyclone separator arrangement.

3. A circulating fluidized bed combustor arrangement according to claim 1, wherein the first cyclone separator arrangement comprises at least one cyclone separator arranged to separate particles having a diameter of greater than about 120 to about 140 μm and the second cyclone separator arrangement comprises at least one cyclone separator arranged to separate particles having a diameter of greater than about 20 to about 40 μm.

4. A circulating fluidized bed combustor arrangement according to claim 1, wherein the second cyclone separator arrangement is connected to another system for processing solid particles.

5. A circulating fluidized bed combustor arrangement according to claim 1, wherein the second cyclone separator arrangement is connected to the combustion chamber of the circulating fluidized bed combustor arrangement for recycling separated solid particles back to the combustion chamber.

6. A circulating fluidized bed combustor arrangement according to claim 4, further comprising a desulfurization system in connection with the combustion chamber, the desulfurization system including means for injecting sulfur sorbent material into the combustion chamber, wherein the second cyclone separator arrangement is connected to the combustion chamber for recycling separated sulfur sorbent material back to the combustion chamber.

7. A circulating fluidized bed combustor arrangement according to claim 1, wherein the means for injecting NOx reducing agent injects ammonia into the exhaust gases and is arranged immediately upstream of the selective catalytic reduction system.

8. A circulating fluidized bed combustor arrangement according to claim 1, wherein the second cyclone separator arrangement is provided with heat recovery means.

9. A circulating fluidized bed combustor arrangement according to claim 1, wherein the second cyclone separator is of an uncooled construction.

10. A circulating fluidized bed combustor arrangement according to claim 1, wherein the first cyclone separator arrangement consists of one cyclone separator and the second cyclone separator arrangement connected to the first cyclone separator arrangement consists of two cyclone separators.

11. A circulating fluidized bed combustor arrangement according to claim 1, wherein the selective catalytic reduction system for removing NOx comprises a group of parallel flow channels having a catalytic material on its respective surfaces.

12. A method of operating a circulating fluidized bed combustor arrangement, the method comprising:
   combating fuel material in a combustion chamber of a circulating fluidized bed reactor in a suspension of solid particles of a circulating fluidized bed;
   passing a mixture of gases and solid particles from the combustion chamber to a first cyclone separator arrangement and separating a first fraction of the solid particles from the gases;
   returning solid particles separated in the first cyclone separator arrangement via a solid particle return system from the first cyclone separator to the combustion chamber;
   passing the gases from which the first fraction of the solid particles has been separated further in the process as exhaust gases;
   recovering heat from the exhaust gases in a water/steam heat exchanger section arranged after the first cyclone separator arrangement in a flow path of the exhaust gases;
   removing NOx from the exhaust gas by passing the exhaust gas through a selective catalytic reduction system arranged into the flow path of the exhaust gases after recovering heat from the exhaust gases;
injecting ammonia into the exhaust gases upstream of the selective catalytic reduction system; and separating a second fraction of the solid particles from the exhaust gases in a second cyclone separator arrangement provided downstream of the first cyclone separator arrangement, prior to recovering heat from the exhaust gases.

13. A method of operating a circulating fluidized bed combustor arrangement according to claim 12, wherein, in the first cyclone separator arrangement, particles having a diameter of greater than about 120 to about 140 µm are separated from the exhaust gases and, in the second cyclone separator arrangement, particles having a diameter of greater than about 20 to about 40 µm are separated from the exhaust gases.

14. A method of operating a circulating fluidized bed combustor arrangement according to claim 12, wherein the solid particles separated in the second cyclone separator arrangement are at least partially passed to another system for processing solid particles.

15. A method of operating a circulating fluidized bed combustor arrangement according to claim 12, wherein the solid particles separated in the second cyclone separator arrangement are at least partially recycled back to the combustion chamber of the circulating fluidized bed combustor.

16. A method of operating a circulating fluidized bed combustor arrangement according to claim 15, further comprising injecting sulfur sorbent material into the combustion chamber of the circulating fluidizing bed combustor, separating unreacted sulfur sorbent material in the second cyclone separator arrangement and recycling at least a portion of the unreacted sulfur sorbent back to the combustor.

17. A method of operating a circulating fluidized bed combustor arrangement according to claim 12, further comprising injecting ammonia into the exhaust gases immediately upstream of the selective catalytic reduction system.

18. A method of operating a circulating fluidized bed combustor arrangement according to claim 10, further comprising recovering heat from the exhaust gases after passing the second cyclone separator arrangement.

19. A method of operating a circulating fluidized bed combustor arrangement according to claim 12, further comprising passing the exhaust gases through the second cyclone separator without substantially cooling the exhaust gases.

20. A method of operating a circulating fluidized bed combustor arrangement according to claim 18, wherein heat from the exhaust gases is recovered after passing the second cyclone separator so that the selective catalytic reduction system is operated at 450-500°C.

21. A method of operating a circulating fluidized bed combustor according to claim 19, further comprising injecting ammonia or urea before the first cyclone in the temperature window of 760-950°C to reduce NOx emission through a selective non-catalytic reduction process.

22. A method of operating a circulating fluidized bed combustor arrangement according to claim 19, wherein both a selective non-catalytic reduction process system and a selective catalytic reduction process system are employed to achieve maximum NOx reduction efficiency.

23. A method of operating a circulating fluidized bed combustor arrangement, the method comprising:

- combusting fuel material in a combustion chamber of a circulating fluidized bed reactor in a suspension of solid particles of a circulating fluidized bed;
- passing a mixture of gases and solid particles from the combustion chamber to a first cyclone separator arrangement and separating a first fraction of the solid particles from the gases;
- returning solid particles separated in the first cyclone separator arrangement via a solid particle return system from the first cyclone separator to the combustion chamber;
- passing the gases from which the first portion of the solid particles has been separated further in the process as exhaust gases;
- recovering heat from the exhaust gases in a water/steam heat exchanger section arranged after the first cyclone separator arrangement in the exhaust gas flow path;
- separating a second fraction of the solid particles from the exhaust gases in a second cyclone separator arrangement provided downstream of the first cyclone separator arrangement prior to recovering heat from the exhaust gases;
- injecting ammonia into the exhaust gases upstream of the selective catalytic reduction system;
- removing NOx from the exhaust gas in a selective non-catalytic reduction process by reacting a first portion of the ammonia injected;
- removing NOx from the exhaust gas in a selective catalytic reduction process by passing the exhaust gas through a selective catalytic reduction system arranged into the exhaust gas flow path after recovering from the exhaust gases and reacting a second portion of the ammonia injected; and
- injecting sulfur sorbent material into the combustion chamber of the circulating fluidized bed combustor, separating unreacted sulfur sorbent material in the second cyclone separator arrangement and recycling at least a portion of the unreacted sulfur sorbent back to the combustor.

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